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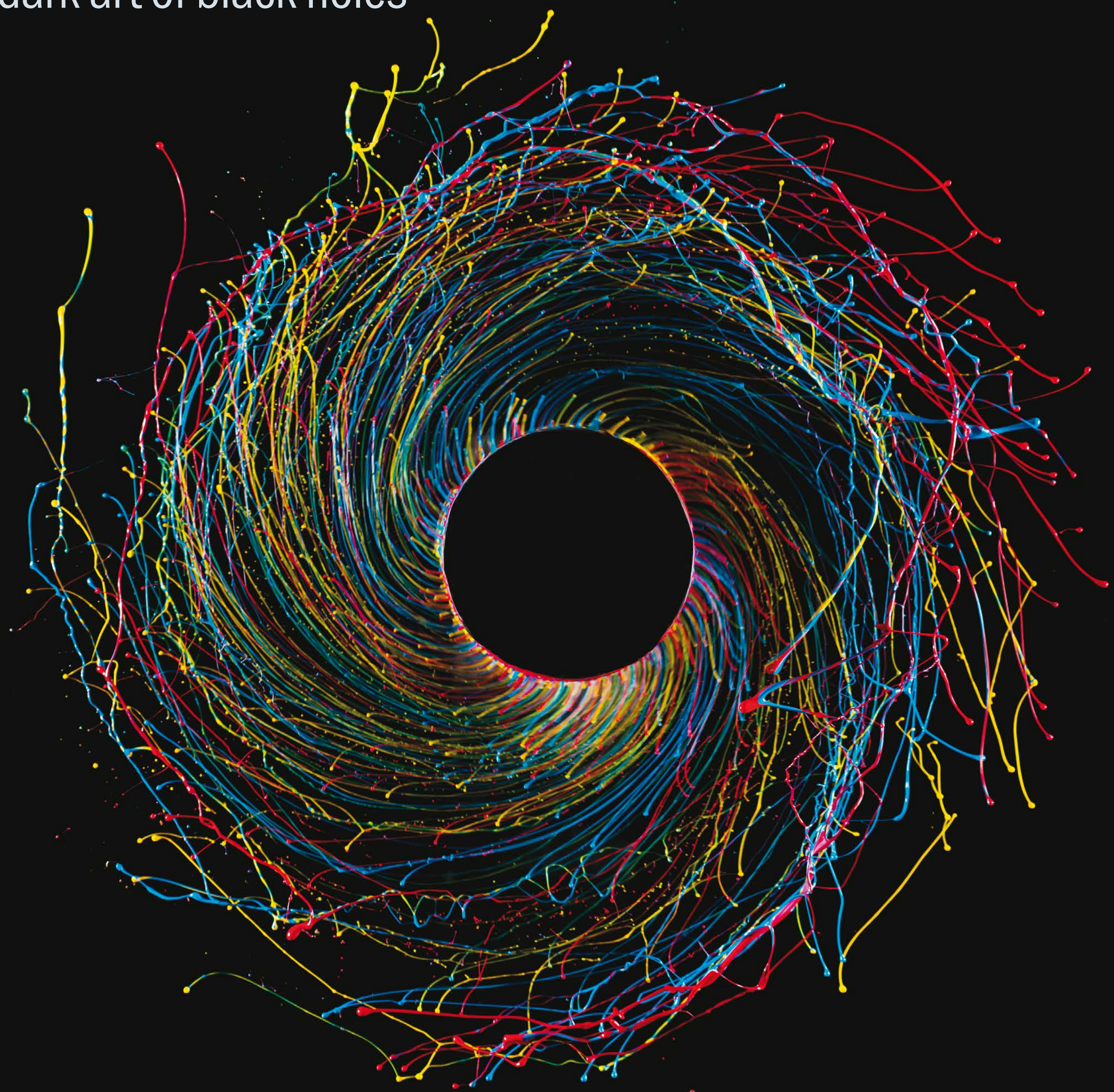
May 2026

Visualizing the invisible
The dark art of black holes



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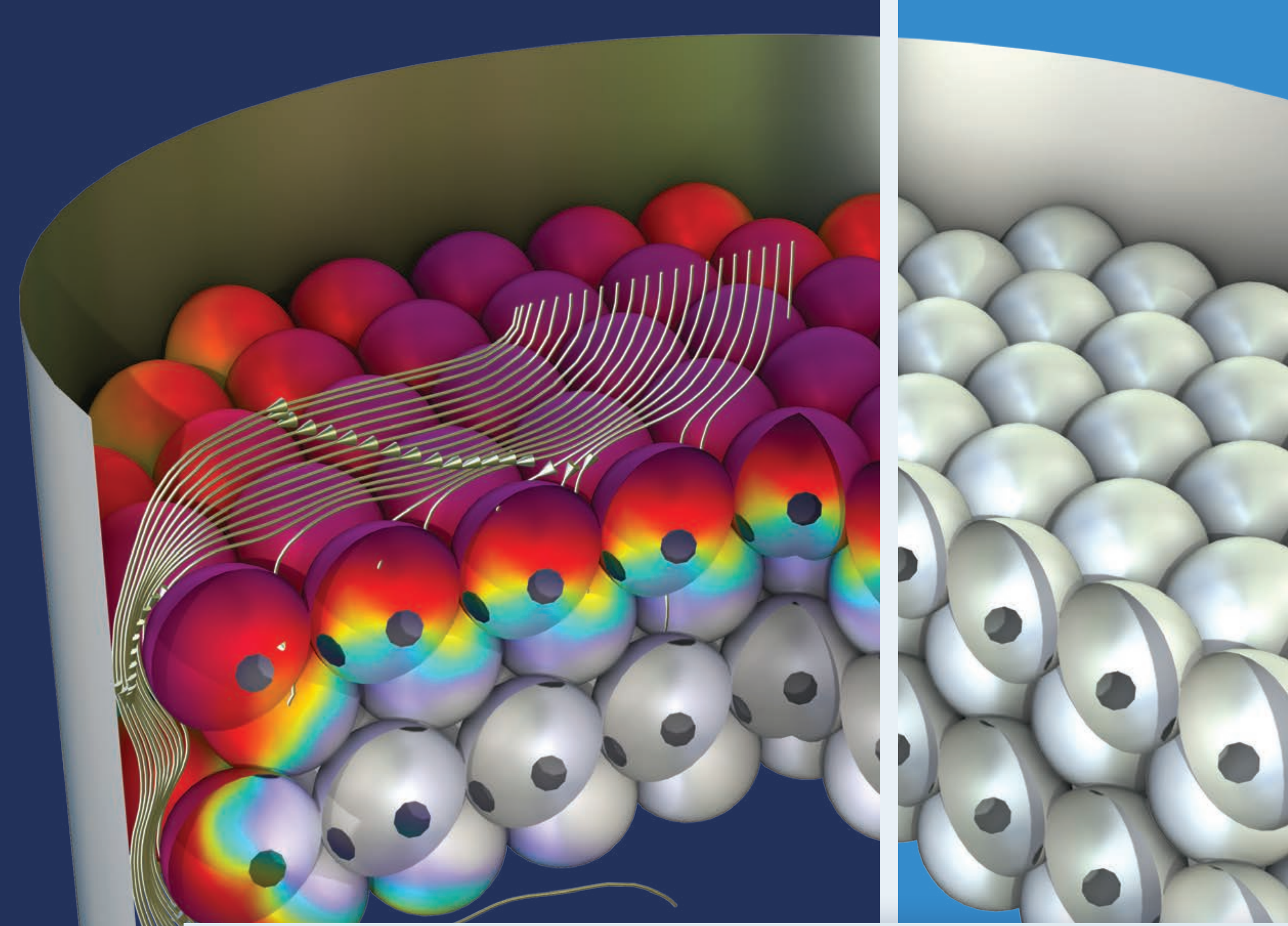

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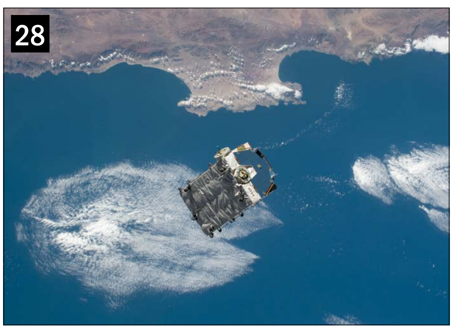

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20 On the cover
Visualizing the invisible: the dark art of black holes. (Fabian Oefner 2014 *Black Hole, No. 2.* Inkjet print, 80 × 120 cm. Courtesy of the artist)

Time for a change

Eagle-eyed readers will notice a few tweaks to *Physics World* magazine this month

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Physics World has long been seen as the world's best physics magazine, keeping you informed about what physicists are up to in a timely, entertaining and trusted fashion. But surveys and feedback tell us there's more to *Physics World* than that. The magazine is also a reminder of why you love physics and studied it in the first place. It's what keeps many of you connected to the rest of the physics community – especially if you're at the start of your career, have moved into a different area, or taken retirement.

At the same time, we know how much you value *Physics World* magazine as one of the benefits of being a member of the Institute of Physics (IOP). We're therefore introducing more coverage of what the IOP, as your member society, is doing to support the physics community. This issue looks at its work with the food-physics community (p5), while over the next few months there'll be an interview with new president Paul Howarth and coverage of the IOP's Impact reports on topics including medical physics, AI and metamaterials.

The tweaks to *Physics World* are also driven by changing reading habits as we spend ever-more time online. We're all used to jumping on our phones for the latest news stories, which we don't expect to read in a monthly publication, by which time they're often stale and out of date. We're therefore reshaping *Physics World* magazine on longer-form features, analysis, interviews, careers and opinion – giving you the time and space to think about topics more deeply.

We're still reporting on all the latest physics news and the best new physics research papers. You'll find that coverage on the *Physics World* website, where it's always been. In fact, the website has a lot more goodies than we can fit in this magazine. You can now enjoy a new interactive puzzles area, including quizzes, crosswords, jigsaws and word games. One of the crosswords – based on a recent *Physics World* feature on the geophysical impact of climate change – appears in this issue as a taster (p52). Online you can also listen to the *Physics World Weekly* and *Physics World Stories* podcasts.

Perhaps best of all, especially if you hoard your copies of *Physics World* at home, the *Physics World* website now provides IOP members with access to a digital archive of issues going back to 2014. If you haven't already, why not explore some great features you may have missed, which range from the quantum Cheshire cat (June 2025) and the physics of sheep (November 2024) to a three-part series on dark matter and another on laser cooling. The issues can be accessed in either a digital flipbook or as individual HTML articles, but we are looking into alternative formats as part of our ongoing website-development programme.

Rest assured that *Physics World* magazine is here to stay and there will be no drop in our editorial standards. Consider this month's changes as an evolution, not a revolution.

Matin Durrani, editor-in-chief, *Physics World*

AUDIO Listen to *Physics World* editors discuss highlights of the May magazine

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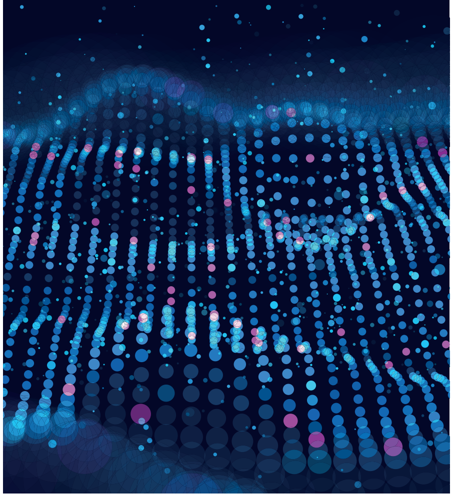

Tasty time ahead for food physics

As the food physics group of the Institute of Physics notches up 10 years of engagement between academia and industry, **Joe McEntee** explores how food physicists are delivering a more sustainable food system while helping manufacturers to reduce costs

Food physicists have a lot on their plate just now. Across academia and industry, the community faces systemic challenges, not least the obesity epidemic, mounting health-and-safety concerns around ultra-processed foods, and the regulatory backlash against plastic food-packaging waste.

The war in the Middle East is another uncomfortable wake-up call. While the effective closure of the Strait of Hormuz to commercial shipping has sent oil and gas prices soaring, that strategic choke point has also shut off around one-third of the seaborne trade in fertilizers, fuelling price spikes and warnings of global food shortages to come.

All these factors will intensify the push from policymakers and the public for a more sustainable "food system". The goal is to make better use of water, energy and raw materials, while minimizing environmental impacts like deforestation and pollution.

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Sweet spot
Through its food physics group, the Institute of Physics brings physicists working in the food sector together and represents their views to funders and policymakers.

What's cooking?

The food-physics community is a diverse mix of senior academics, early-career researchers and R&D scientists from the food-and-drink industry. Many of them came together recently in Leeds, UK, at Food Physics X – the 10th annual conference of the food-physics group of the Institute of Physics (IOP). Top of the agenda was how the food industry can deliver nutritious and tasty products, while at the same time accelerating technology and process innovation to cut manufacturing costs and time-to-market.

"Food physics and its multidisciplinary practitioners have a key enabling role here," says Zachary Glover, an industrial biophysicist who has chaired the IOP's food physics group since 2021. "Collectively, the challenge lies not just in improving food security and resilience of supply, but also in supporting industry R&D initiatives towards enhanced productivity, circularity [to minimize waste] and environmental sustainability."

Glover is optimistic about the food industry's ability to reinvent itself, especially when it comes to addressing the growing regulatory and geopolitical challenges through new digital technologies. "AI and machine learning are already transforming best practice in research, publishing and education," he says. "Our task as a food physics community is to leverage what these tools have to offer to boost innovation and minimize the risks of bland homogeneity in our at-scale food production."

Yet reinvention for food manufacturers will not be easy. The path to smart manufacturing (what's sometimes dubbed "industry 4.0") is more of a digital evolution than a revolution – whether that's using "cobots" to reduce physical loading during manual-handling operations or exploiting AI to control manufacturing processes.

"Nationally, there is a huge sunk cost in the food industry's existing manufacturing asset base," says Glover. "This cannot and will not be replaced wholesale, while economic and geopolitical factors will ultimately dictate the pace at which industry is able to disrupt itself with new digital technologies."

Out of the lab, into the factory

Despite the conservatism of those in the food industry, academics are pressing ahead, with physics-informed AI and machine learning (PIAI and PIML) fuelling both technology push and food-process innovation. According to University of Leeds food physicist Megan Povey in her keynote presentation at Food Physics X, physicists have integrated fundamental models of transport phenomena with PIML to create hybrid model systems that are both data-efficient and physically consistent. "The payoff is a reduced reliance on costly trial-and-error experimentation," she says.

Povey uses ultrasound spectroscopy for food characterization and ultrasound processing in food manufacturing R&D. She also focuses on the computer and mathematical modelling of foods, pointing out that PIML can now solve complex partial differential equations relevant to heat transfer, mass transfer, microbial inactivation and structural changes, even when limited data are available.

IOP/Rob Watson Photography

Multidisciplinary by nature Across two days of talks, poster sessions and panel discussions, Food Physics X in Leeds earlier this year provided a forum for networking, collaboration and knowledge transfer between academic and industrial scientists.

IOP/Rob Watson Photography

Talent pipeline Visibility and recognition of early-career researchers was a defining theme of the Food Physics X conference in Leeds.

"PIML has improved the accuracy of forward and inverse modelling, accelerated virtual prototyping of food products, and increasingly supported the development of real-time digital twins [interactive computer simulations] for process optimization," Povey told delegates at Food Physics X. She and her colleagues are putting such advances to practical use at the Leeds Food AI Lab, which brings together experts from a range of disciplines in sensing, machine learning, optimization and life-cycle assessment.

By training PIML models on food-system-relevant data generated using the lab's "sensor-fusion" capability, the Food AI Lab and its research partners are, for example, transforming variable, low-value agri-food residues into reliable sources of sustainable protein – what's known as "agri-food waste upcycling". The lab also uses near-infrared spectroscopy and machine learning to detect allergens in powdered food and applies ultrasonic sensing, machine learning and Bayesian optimization to cut the cost and environmental impact of industrial cleaning processes.

"We are engaged in creating a more sustainable food industry at AI Food Lab," Povey says. "Along the way, new measurement techniques, advances in mathematics, plus PIAI and PIML innovations will transform our understanding of the physics of food and nutrition."

For both Povey and Glover, who this summer ends his five-year stint as IOP food physics chair, being part of an organization that promotes and defends physics is integral to their professional identities. "With the help of our colleagues at the IOP, we weathered the COVID years with online events and have had three strong in-person annual conferences since then," says Glover. "The feedback on our conferences is fantastic and it genuinely feels like our members want to be there, engaging face-to-face with their peers."

For Glover, the food physics group is all about bringing like-minded scientists and engineers together, with a self-sustaining community of shared practice among the main achievements during his tenure as group chair. "Looking ahead, the group will continue to educate physicists in academia about the richness of questions in food science," he says. "Just as important, we will engage industry scientists about the role of physics as a 'quiet enabler' of technology translation and food-product innovation."

Joe McEntee is a consultant editor based in South Gloucestershire, UK

Food physics: the next generation

One notable feature of the IOP food physics group's annual gathering is the prominence given to early-career researchers. Food Physics X in February was no different, with the work of two early-career scientists recognized by best poster awards.

Best oral poster: Molly Massey, University of Leeds, UK

The crystallization and melting behaviour of blends of cocoa-butter equivalents and milk fats using small- and wide-angle X-ray scattering (SAXS/WAXS).

The texture, gloss and shelf-life of chocolate are largely governed by fat crystallization during production, with developers' ability to control the various crystalline forms (or "polymorphs") of cocoa butter underpinning the quality of the end-product. However, growing demand for plant-based alternatives means that food manufacturers want to replicate the qualities of cocoa butter using cocoa-butter equivalents (CBEs).

With this in mind, Massey is using synchrotron SAXS/WAXS experiments to evaluate the role of anhydrous milk fat – traditionally used in milk chocolate to influence texture, polymorphic transitions and melting profiles – on the crystallization behaviour of CBE blends. Her

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long-term goal is to replicate those structural and thermal effects in dairy-free material systems that rely on milk-fat replacement blends.

Best paper poster: Ashley Roye, King's College London, UK

Biomimetic modelling of oral mucus microstructure for understanding lubrication and taste transport.

Roye is investigating the interaction between the mouth's salivary/mucus layers and "tastant" molecules, which are food compounds that trigger the sensation of taste. Her research focuses on how mucins (large protein molecules with carbohydrate attachments) in saliva and the mucosal lining mediate tastant transport to the taste buds and, in turn, how that process influences lubrication, mouthfeel and textural sensation of different food components.

Academia must get closer to industry

With funding cuts hampering academic science budgets in the UK and US, **Mark Procter** says that industrial science can play a pivotal role in supporting research

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Working together Despite many in academia viewing collaboration with industry as peripheral and distracting, there can be many benefits.

Anyone paying even cursory attention to the research landscape in recent months would have noticed the growing turbulence in public science funding on both sides of the Atlantic. In the UK, the research community has been shaken not by a single dramatic cut, but by a prolonged period of budgetary tightening at UK Research and Innovation (UKRI), driven by flat-cash settlements, rising inflation and increasing pressure to redirect funding towards government-defined missions.

Although government ministers continue to emphasize "record" overall R&D spending, UKRI has been forced to make difficult reprioritization decisions, leading to pauses and closures of several schemes across the research councils. The effects are already being felt, with competition for remaining funding intensifying. Success rates are coming under strain and many researchers are facing heightened uncertainty about the viability of pursuing curiosity-driven research.

Globally, the picture is similar. In the US, the National Science Foundation has become a focal point of intense budgetary uncertainty, with proposed reductions and flat-cash congressional settlements placing growing strain on its ability to sustain investigator-led research. In Europe the €95.5bn Horizon Europe programme faces mounting political pressure to demonstrate impact and value for money amid economic uncertainty and competing fiscal priorities.

For academics, these dynamics translate into tougher competition for grants, longer odds of success and an increasing reliance on short-term, project-specific funding rather than stable, long-horizon research support.

Academic science has always been under pressure to deliver more with less. But the current climate feels different. The combination of shrinking government budgets, rising operational costs and increasing competition for limited grants has created a perfect storm. For early-career researchers and established labs alike, the traditional model of securing public funding is becoming unsustainable.

The implications are profound. Without adequate resources, research groups risk losing momentum, empty talent pipelines and stalling innovation. For many the question is no longer "how do we grow?" but "how do we survive?" Yet amid these challenges lies an opportunity: forging deeper, more strategic partnerships with industry.

The path ahead

You may ask the question "why would companies invest in academic research?" The answer is simply innovation. Industry thrives on differentiation and academic partnerships offer a cost-effective way to access cutting-edge science without bearing the full burden of in-house R&D.

Consider the pharmaceutical sector. Drug discovery is notoriously expensive and time-consuming but collaborating with academic labs allows companies to tap into specialized expertise, advanced facilities and novel methodologies. Similarly in energy and materials science, universities often lead the way in developing next-generation technologies that can redefine markets.

Beyond innovation, partnerships also offer credibility. Peer-reviewed publications and independent validation enhance a company's reputation and can accelerate regulatory approval. For industries facing complex challenges; such as sustainability, cybersecurity or quantum computing, academic collaboration is not a luxury; it's a necessity.

So, what can be done to strengthen academic collaboration with industry? The first step is a subtle but important mindset shift. For many researchers, academia has traditionally operated with a strong internal focus, where industry engagement is seen less as undesirable and more as additional – something that sits alongside core research rather than at its centre.

This isn't about viewing collaboration as secondary or compromising, but about recognizing that aligning fundamental research with industry priorities takes time and sustained effort. It introduces new constraints, different timelines and added complexity into already demanding research programmes.

The challenge, then, is not one of principle, but of practicality. Collaboration is not about box-ticking or "selling out"; it's about creating the conditions in which fundamental research can remain connected, impactful and resilient in an increasingly complex research ecosystem.

Academics should look for companies with long-term goals that align with their research expertise – creating shared value, not just chasing sponsorships. Another aspect to remember is that industry mandates tangible outcomes. While fundamental research remains vital, framing projects in terms of applied benefits can unlock funding.

It is also important that academics learn to communicate impact. Industry leaders speak the language of "minimum viable product", "return on investment" and "risk mitigation". Academics must learn to articulate how their work translates into competitive advantage.

This mindset shift requires effort, but the payoff can be significant in sustained funding streams, access to real-world data, as well as opportunities to test theories in practical settings. When done right, such collaborations also create a virtuous cycle. Academics secure funding and maintain research momentum, while industry gains competitive advantage, joint publications, shared intellectual property and co-developed technologies that strengthen both ecosystems.

Such partnerships can also foster talent development. Graduate students and postdocs gain exposure to realistic problems, enhancing employability and bridging the gap between theory and practice – a critical outcome, given the current bleak outlook for graduate employment worldwide.

For industry, this means access to a pipeline of skilled professionals who understand both scientific rigor and commercial realities. The benefits also extend beyond economics. Collaborative projects often tackle grand challenges – climate change, healthcare, digital security – that no single entity can solve alone. By pooling resources and expertise, academia and industry can drive progress at a scale that matters.

To make this vision a reality, collaboration must be incentivized. Funding agencies can play a pivotal role by enabling grants that include industrial partners, while tax incentives for collaborative R&D could further accelerate uptake.

At the same time, universities must embrace cultural change. Academics must move beyond the notion that collaboration dilutes scientific integrity. Transparency and clear governance can safeguard independence while enabling impact.

The future of academic science may well depend on its ability to align with industry. The current rhetoric from UKRI focuses on return on investment from publicly funded research to meet the UK's industrial strategy.

In a world where resources are scarce and challenges are complex, working together is the only way forward. The coming decade will test the resilience of academic research. Those who cling to old models risk obsolescence. Those who adapt by embracing industry partnerships will not only survive but thrive. The question is not whether collaboration is necessary, but how quickly we can make it happen.

An industrial collaboration 'playbook'

Mark Procter outlines his five principles for building successful partnerships between academia and industry.

1 Align on impact, not just intellectual property
Focus on creating measurable outcomes rather than solely on rigid intellectual property battles. Impact drives funding and reputation for both sides.

2 Define mutual gains early
Establish clear objectives that benefit both academic advancement and industrial innovation. Document these in a collaboration charter before work begins.

3 Streamline governance
Simplify legal frameworks and reduce administrative friction. Negotiating non-disclosure and intellectual property agreements should not take longer than the research itself.

4 Embed talent exchange
Include opportunities for student placements, joint supervision and secondments. This builds trust and creates a pipeline of skilled professionals. Reciprocally, universities should structure their own professional development opportunities in collaboration with industry.

5 Measure success beyond publications
Track metrics such as technology readiness progression, prototype development and demonstrable economic impact, not just journal citations.

Mark Procter is vice-president of science and technology at the UK security firm Rapiscan, e-mail mprocter@rapiscan.com

The importance of ‘giving back’

Mentoring students and people at the start of their careers might seem an irrelevant and time-consuming chore. **Honor Powrie** explains why passing on your skills and expertise to the next generation of scientists and engineers is not just valuable but enjoyable too

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Making a difference Whether done formally or informally, mentoring is a great way to “give back” to the next generation of scientists and engineers to help them solve the challenges of the future.

A couple of months ago I wrote about whether it’s possible to teach the art of entrepreneurship or if it’s a skill that’s innate to individuals. My article led to some invaluable feedback, notably from one reader who said that, yes, of course it can be taught. Not, they said, from formal lectures but mainly through mentoring by people who’ve learned the art of entrepreneurship themselves.

That idea got me thinking about the wider benefit of “giving back” one’s experience to others who could gain from that wisdom. All professional scientists and engineers will have benefited at one time or another from the generous guidance of other people – be they teachers, lecturers, or work colleagues. So perhaps we should think about how we can do the same.

It’s easy to imagine our lives are so inconsequential that we have nothing to teach – and even if we do have something to say, we certainly haven’t got the time to tell others about it. But the value of a professional interaction, however small, should not be overlooked. A timely moment at any career stage can make all the difference to an individual’s professional impact and future success. The scope of opportunity for giving back is broad.

Volunteering and internships

In my experience, local schools are always grateful for career guidance from professionals. Staff at my company, for example, often give career talks at their children’s schools. We take part in events such as assemblies, career evenings or careers weeks and we are currently keen to provide work experience for 16- and 17-year-olds in year 12. If we go ahead, I am sure pupils will be eager to snap opportunities up.

I have also seen the benefit of scientists and engineers developing videos, workbooks and other materials for primary-school children to learn about concepts in science and technology. It is important to make an impact at the earliest possible stage, which is where the talent pipeline starts. Once students are in their teens and have made their subject choices, it becomes hard – if not impossible – to influence them.

Internships are another great way of giving back. For the last eight years, I have been running a data-science internship programme at GE – and I just wish I’d started it sooner. Initially, we offered summer-long placements, but after a year we added year-long roles to the mix. I

The value of a professional interaction, however small, should not be overlooked

Being a member of a professional body is a great way to give back to the community

Back to school Experienced industrialists could opt to become visiting professors – sharing their knowledge and experience with current students.

will be honest, colleagues were hugely sceptical about how much value these roles would bring, but their worry proved unfounded.

The vast majority of our interns have been extremely productive under our guidance and, after finishing, have gone on to secure graduate positions within GE or other tech firms. It's vital, however, that interns are properly supported. As well as being given comprehensive induction and training, interns must be part of an established project team, whose members are always on hand to give guidance, answer questions, and provide the interns with clear tasks and goals.

It's also important to set expectations of professionalism when at work. We are fortunate in GE that interns are taken on as regular employees and so have access to a wide range of employee and company benefits. Interns therefore find it easier to feel part of the company and adopt its ethos. Remember too, that the benefits work both ways. Interns bring you new perspectives and fresh ideas, while also keeping the rest of the team stimulated.

Professional societies and professorships

Being a member of a professional body is also a great way to give back to the community. The Institute of Physics (IOP), for example, has an active volunteer community, along with special interest groups and regional and national branches that are all run by member volunteers, with help from IOP staff. Becoming an IOP volunteer also gives you the chance to influence and help shape the physics community.

You could, for example, get involved with running lectures, seminars, webinars and career outreach events. By meeting like-minded colleagues, you can build your network and give back to the community at the same time. There are some great examples, notably Deborah Phelps, a physicist in engineering who ended up launching the IOP's girl-guiding badge.

For more experienced industrialists, another way to give back is to become a visiting professor. Being fortunate enough to hold such a position myself, they let you go back to university and share your knowledge and experience with current students. It's invaluable for universities too, allowing students to learn what real-life careers look like and what skills they might need beyond the technical knowledge gained during a degree.

Visiting professorships tend to be awarded directly by universities. But competitive awards exist too. The Royal Academy of Engineering, for example, runs a scheme that brings engineers, entrepreneurs, consultants and other industry insiders into UK universities to boost undergraduate engineering education. Covering areas that would appeal to physicists, such as energy, materials and electronics, the scheme lets experts deliver face-to-face teaching, mentoring and curriculum development for three years.

The Royal Society, meanwhile, runs an entrepreneur-in-residence scheme that's been taken up by people like Fiona Riddich, who originally studied maths and physics before joining the energy industry. She's mentored students at the University of Edinburgh and developed a project called Energy@Edinburgh to raise awareness of researchers' work, promote interdisciplinary exchange, grow staff understanding of the energy market, and encourage innovation and translation of research.

I have only scratched the surface of what can be done for the good of our scientific and engineering community, but there is plenty of opportunity and few, if any, barriers to entry. I can't emphasize enough the importance of doing this, especially for growing our pipeline of technical breakthroughs and developing talented people for the future.

My challenge to you is to tell your colleagues what you're already doing to "give back" – and why. And if you're doing nothing to give back, now is the perfect time to get started.

Honor Powrie is an engineer who is now senior director for data science and analytics at GE in Southampton, UK. She is writing here in a personal capacity

Penny for your thoughts

With the Trump administration having minted America's last-ever one-cent coins, **Robert P Crease** wonders what the loss of the US penny will do to science education

Let us mourn the demise of the American penny. With each of the one-cent coins costing about three cents to make, it was "wasteful" to keep producing them, pronounced President Trump. US pennies won't vanish soon. While the last was minted in November 2025, about 250 billion will remain in circulation for a time despite the rising number of cash-free transactions.

The US penny has been around since 1793. Lamenting its passing is faintly obscene compared to other things that the US government has done lately, such as terminating science agencies, cutting jobs, and slashing budgets, environmental regulations and vaccine research. But I can't stop thinking about what the penny meant to my own science education.

Lasting legacy The final US pennies were minted in late 2025, having long been used as an educational prop by science teachers in American schools.

Science collaborators

Pennies, which until the early 1980s were 95% copper, taught me about corrosion. I learned, for instance, that the Statue of Liberty's green colour is due to oxidized copper. At school, we were taught how to make pennies a light shade of green by immersing them in salt and vinegar; a plant food such as Miracle Gro works even better as it contains ammonia. We were then instructed to figure out how to clean off the green, discovering that an acid like lemon juice did the trick.

When I placed a drop of water on the surface of a penny, the dome-like shape it adopted – caused simply by surface tension – was an impressive sight. My first lessons on ions, meanwhile, involved placing pennies and steel nails in a bath of salt and vinegar: the nails got electroplated with copper; the pennies with zinc.

We also had to determine the density of pennies, which are 19 mm in diameter and 1.52 mm thick, by submerging them in a graduated cylinder to find their volume and then weighing them to determine their mass. From 1983 – years after my high-school career – this exercise turned more interesting still because pennies became 97.5% zinc and were only plated with copper so you had to be eagle-eyed to tell old and new apart.

Pennies were indispensable lab props too. All the kilogram weights for mechanics experiments were bags of 400 pennies (the 1983+ penny weighing exactly 2.50 g). They were great for coin-tossing in statistics classes too, although I assume other coins gave the same result, even if that was an experiment we never tried.

The humble penny was effective for all these uses because it wasn't some piece of lab equipment manufactured by an educational company but a familiar part of our world. The coins were cheap and available, and nobody cared if you lost them or took a few home.

You could stick pennies under a leg to prop up a wobbly table. They made makeshift washers if you punched in a hole and inserted nails or screws. If you were bored by the hand-cranked penny-squishing machines at tourist sites and amusement parks whose results are fully predictable, a more exciting way to deface currency would be to lay pennies on railroad tracks and hunt for the results in the stones after the train passes, though never do this because it's dangerous.

The humble penny wasn't some piece of lab equipment manufactured by an educational company but a familiar part of our world

Unit value

Pennies taught me something indirectly. After a breakup, my ex left abandoning some clothing, a cat and a large bowl containing literally thousands of pennies. The clothes I could throw out and I had to learn to love the cat. But the bowl?

I tried to put it at the bottom of my closet, but the damned thing continued to haunt me. Should I toss the bowl and its contents in the garbage? Wasteful, unenvironmental and avoidant. Stuff the pennies into 50-cent coin-roll holder or take them to a coin-counting kiosk in a bank, and then present them to a teller? Psychologically unsatisfying.

No, I had to deal with the pennies doing with them what they were meant for. I must spend them. At a bar one night I tried to pay the tab using all pennies. They were legal tender, right? The bouncer was summoned. One night a taxi driver furiously threw my pennies back at me, accusing me of treating him like a waiter. I was astonished that he thought I was disrespecting him rather than engaged in post-breakup, self-absorbed, infantile behaviour.

I could only use the fundamental unit of US currency in anomalous circumstances that I had to generate myself. In those days the *New York Times* cost 35 cents and I managed to befriend a sympathetic newsstand worker who, a few times a week, was willing to let me buy it all in pennies. He'd cheerfully greet me with "Here come my pennies!" and claimed I was becoming a better person now I was greeting vendors with smiles, not scowls.

I learned to work the monetary system methodically. For things that cost a little over 25 cents, I used a quarter and then pennies for what was left; for things that cost a little over a dollar I handed over a bill and the rest in pennies. I'd choreograph my purchases in advance so that I could use the appropriate lesser unit of currency plus pennies.

I often exploited the fact that sales tax in the US is only added on at the till, which means that something priced $2 with a sales tax of 6.5% will be $2.13 when you pay the cashier. So I'd hunt around in my pocket for a moment, and then in feigned chagrin say that I only had pennies, and hand the cashier the 13 of them that I had carefully calculated beforehand would be needed.

Soon, keeping exacting track of purchases, I managed to spend an average of about 200 pennies a week. From day to day and even week to week the pile in the bowl barely dwindled. But, finally, after a little less than a year only a handful remained. I was thrilled – it was better than seeing a therapist.

I managed to befriend a sympathetic newsstand worker who, a few times a week, was willing to let me buy the *New York Times* all in pennies

The critical point

You might think that the moral I'm about to draw is the need for faith in incremental change – that, penny by penny, you can move mountains. That's certainly the lesson teachers urge on you if you're learning a foreign language or playing a musical instrument.

No, I was instead moved by the humbler experience of valuing an entire system of units moored to a stable, familiar, simple but all-important base unit that you can literally count on.

I still value that lesson, though it's less concrete than what I learned from corroded, nailed or squished pennies.

Robert P Crease is a professor in the Department of Philosophy, Stony Brook University, US; e-mail robert.crease@stonybrook.edu; www.robertpcrease.com; his latest book is *The Leak* (2022 MIT Press)

Invisible force of nature

Kate Ravilious reviews *The Breath of the Gods: the History and Future of the Wind* by Simon Winchester

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Dangerous force The wind shapes desert dunes, as it's doing here, in the Almaty region of Kazakhstan.

In recent years the news has been dominated by devastating hurricanes, cyclones, tornadoes, wildfires and floods, and data show that these hazardous events are increasing in frequency and strength. It is clear that our weather is becoming more extreme, with a warming world adding more energy to the atmosphere and increasing the power of these wind-fuelled events.

With this in mind, Simon Winchester's opening question in *The Breath of the Gods: the History and Future of the Wind* might surprise readers: are Earth's winds slowing down? There was, indeed, a decrease in wind speeds over land between the 1980s and 2010, which was ominously dubbed the Great Stilling. In fact, observations show a decrease in average wind speeds over land of between 5 and 15% over the last 50 years. So what is going on?

Winchester – a writer and journalist with a background in geology – starts his quest to discover more atop the windiest place in the world, the summit of Mount Washington. With delicious irony, he finds the anemometers are still and a very rare calm hangs in the air.

He goes on to build the case for exceptional weather becoming the norm. He covers recent examples of extreme wind events, such as the exceedingly hot and dry Santa Ana winds of January 2025, which fed the dramatic and devastating wildfires that ripped through suburbs of Los Angeles; the record-breaking storms that pounded Europe during 2024 and 2025; and the freak tornado in March 2023 that killed 17 people and razed the town of Rolling Fork, Mississippi, to the ground.

Ever-present element

This book isn't simply a tour of wind-related disasters, however. Winchester takes us back through thousands of years of human history, to explore how wind influenced some of the earliest civilizations. The first recorded mention of the wind arose 5000 years ago and comes from the ancient kingdom of Sumer (now south-eastern Iraq). People there identified four different prevailing winds and attributed their characteristics to four different gods. This classification system persists to this day, with our familiar north, east, south and west winds originating from these mythological four Mesopotamian winds.

For much of history humans have made use of the wind: from propelling pioneering populations in tiny boats across the Pacific Ocean some 5000 years ago, to enabling human flight; from milling grain and pumping water with windmills, to using them to generate energy. But it is only in more recent times that we have started to map and understand the major winds on our planet and the role they play in making it habitable.

Winchester romps through the science. We learn how the wind has pummelled, shaped and moulded the Earth since time immemorial, and how the winds work in tandem with the oceans, constantly transporting energy from equator to poles and preventing the planet from overheating. He also introduces key characters along the way, such as Brigadier Ralph Bagnold, a British army engineer. Bagnold used wind tunnel experiments and his extensive desert experience to understand the physics of windblown grains and the circumstances that create everything from tiny ripples in sand, to mighty marching barchan dunes.

It is only in more recent times that we have started to map and understand the major winds on our planet

But it is when the wind works against us that its might is truly revealed, and Winchester devotes an entire chapter to inclement winds. He starts by transporting us into the wretched five years of the American Great Depression in the 1930s, when terrible dust storms tore the topsoil from the prairie states of Oklahoma, Texas, Kansas, Colorado and Nebraska, resulting in starvation and mass migration. We hear how the arrival of the settlers and farming technology triggered this tragedy, with steel-bladed ploughs ripping through the soil and tearing up the grasses that had previously glued the soil to the land.

However, this is a tale that ends well, with President Roosevelt taking sound advice and devising an audacious plan to fix it. As a result, some 220 million trees were planted in a series of windbreaks stretching from the Canadian border down to central Texas. These restored prosperous and stable farmland to the American Midwest, and survive to this day.

Writing a book about this invisible force of nature could be stuffy, but Winchester brings his trademark curiosity and storytelling to the fore. He whisks readers through history and around the world, inserting himself into the story and pulling out the human impacts that bring the topic alive.

But while it's a thoroughly enjoyable read, *The Breath of the Gods* lacks a thread to hold the book together. And most frustratingly, it fails to really return to answer the opening question about what's behind the slowing winds. I would have liked a bit more science – particularly in understanding the impact that climate change is having on the wind – but for those looking for an accessible read with lots of fascinating weather anecdotes to regale friends with, this book won't disappoint.

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Kate Ravilious is a freelance science writer in the UK

Copenhagen reinterpreted

Chris Sinclair talks to Michael Frayn about a revival at Hampstead Theatre in London of his classic science play *Copenhagen*, directed by Michael Longhurst

Marc Brenner

Stage success Damien Molony (as Werner Heisenberg), Richard Schiff (Niels Bohr – with cardigan) and Alex Kingston (Margrethe Bohr) in the revival of Michael Frayn's *Copenhagen* at the Hampstead Theatre in London.

When Werner Heisenberg retreated at daybreak to an isolated rock on the island of Helgoland in June 1925 to contemplate his development of quantum physics, he might well have been surprised to know that this moment would be recreated by an actor perched on the back of a chair in a pool of water on a stage over 100 years later.

However, this is exactly what happens in a revival of Michael Frayn's play *Copenhagen*, currently at Hampstead Theatre in London.

The play explores Heisenberg's visit to see Niels Bohr in Nazi-occupied Copenhagen in 1941 and features just three characters: Heisenberg, Bohr and Bohr's wife Margrethe. The intentions surrounding Heisenberg's visit have always been unclear, with this uncertainty being central to the play, which was first staged to critical and popular acclaim at the National Theatre, London, in 1998.

The initial success of *Copenhagen* came even as a surprise to its writer Michael Frayn. "When I wrote it, I didn't think it would even be staged," he admitted in an interview with *Physics World*. Eventually, *Copenhagen* went on to receive many accolades, including a Tony Award for Best Play, and enjoyed over 300 performances in London and New York.

Directed by Michael Longhurst, the new production at Hampstead Theatre remains largely faithful to previous versions, with the three characters inhabiting a circular revolving stage. Joanna Scotcher's set design intriguingly surrounds them with a large pool of water, referencing the role of the sea in the play as well as perhaps the heavy water that surrounds a fission reactor.

Longhurst told me how struck he's been by the level of detail in the text. "While Frayn is super conscious of this as an act of fiction and theoretical imaging, I don't think I've ever worked on a play that feels like it's been as rigorously researched," he says.

"I think there's a real pleasure and opportunity as a director, when you're staging plays that are tapping into scientific principles. There is a beautiful probing parallel between the uncertainty of intention and Heisenberg's uncertainty principle."

Heisenberg's involvement in what became the German nuclear-bomb programme is likely to have been a significant factor in his seeking to meet with Bohr, but the beauty of the play is the uncertainty behind the real motivation for the meeting.

As Frayn told *Physics World*: "The play is about the elusiveness of human intention, so I don't claim to have a settled view of Heisenberg's." However, Frayn hints that he is most persuaded by Heisenberg's own account, which he gave many years later, that he wanted to warn the Allies about Germany's plan to build a bomb, rather than trying to get information from Bohr to help the Nazi programme.

"Bohr's confirmation in his unsent letter [in 1957]," says Frayn, "that Heisenberg had in fact overridden all normal obligations of wartime secrecy to tell him that Germany was doing research on a nuclear weapon – and that he now believed it was in theory possible to build one – seems to me to go some way to reinforcing the account that Heisenberg himself gave later of his intentions in seeking the meeting in 1941."

As for the new revival at Hampstead, Longhurst says it is a chance "to engage with an incredible play that hasn't been seen in London since that original production".

Marc Brenner

Round and round The revival of *Copenhagen*, which focuses on the 1941 discussion between Niels Bohr (left) and Werner Heisenberg (right), with Margrethe Bohr looking on.

"I'm very proud of the cast that we've assembled in Damien Molony, Richard Schiff and Alex Kingston, who I think are individually and collectively brilliant. I guess what is thrilling about the play when you see it live, and it is three bodies in a contained space, is watching them shift between prosecutor, witness and judge. That triangle of relationships is constantly shifting. I like to imagine them as three entangled souls with an unanswered question."

Chris Sinclair is a physicist in the UK, who runs Science Centre Stage, which supports the depiction of scientific ideas and the history of science in theatre

Feedback

Letters and comments that appear here may have been edited, and do not necessarily reflect the views of *Physics World*. Please send us your feedback by e-mail to pwld@ioppublishing.org

How to be an entrepreneur

In response to the Transactions article by Honor Powrie (February p15), which examined if entrepreneurship is an innate talent – or something that can be taught.

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Taking flight What skills do entrepreneurs need to get their ideas off the ground?

Successful entrepreneurs are people with unique talents who respond in a daring and timely fashion to a specific set of circumstances in which they – often serendipitously – find themselves. It's perfectly possible to teach entrepreneurship – not through formal, structured courses but by successful entrepreneurs providing informal mentoring to others.

As Powrie observes, scientists and engineers have a range of skills that are useful in an entrepreneurial environment, including the ability to innovate and invent. Those very attributes, however, mean that they're too often focused on trying to improve a product rather than the requirements of the customer.

Any entrepreneurial company needs a range of skills and the calculated risk management that comes from a formal training in engineering can be key to success. In the right environment, the creative tension between entrepreneurs, who are focused on market-pull, and scientists and engineers, who have to deliver a product, can be stimulating.

Launching products too early – before the risks associated with performance, reliability, cost and ease of manufacture have been fully quantified – can be disastrous. But it can be just as financially devastating to miss a market opportunity by not accepting and managing an imperfect level of engineering knowledge. Balancing those risks and rewards, while remaining totally convinced about the product or service, is vital for any early-stage firm.

Some formal training can help scientists or engineers to understand what entrepreneurship is all about, but a better route to becoming an entrepreneur is a willingness to take personal financial risk, potentially by joining – or investing in – a start-up firm with a financial security horizon of typically 18 months. The skills and instincts of scientists and engineers are critical to business survival and growth in this environment – but being part of a start-up can be almost intoxicating.

Brian Tanner
Durham University, UK

I applaud Powrie's attempt to distinguish between entrepreneurship and engineering skills, but it's worth adding that the ISO 56000:2020 standard – which is well worth adopting – defines innovation as "a new or changed entity, realizing or redistributing value". Value in this context can mean either monetary or societal value – and innovators should be concerned with both.

Successful entrepreneurs are not risk takers. Like running a giant experiment, they will ask hundreds – if not thousands – of customers for their opinion before formulating a set of user needs, from which product requirements and product specifications are derived. An unsuccessful entrepreneur, however, will ask just $n = 1$ customers, which is a big risk.

Speed to market is also not necessarily a primary driver especially in regulated markets, such as aerospace or pharmaceuticals, where a product or service can literally kill a customer. The same is true for products where quality is the primary driver according to customer feedback.

Engineers and entrepreneurs will usually work on separate parts of the innovation process. But really great engineers, who can do both and see it as a continuum, often make fantastic entrepreneurs.

Jane Theaker
SpinXperts Ltd, Chester, UK

When engineers and physicists say something is "risky", they're often referring to the need to make quick decisions based on imperfect, incomplete and uncertain information. This is especially true when launching a new business, where uncertainty dominates.

Thankfully there are tools and techniques to help, such as the Lean Canvas methodology, which lets each part of a business model be treated as a testable hypothesis that can be accepted or rejected by gathering evidence.

It's also vital to recognize that technical merit is not the only factor contributing to commercial success. Entrepreneurship is about spotting a commercial opportunity in some piece of technology, working out who the buyer is, what they will pay, and what the cost of servicing their need is. In other words, much of it comes down to selling.

However, I still believe it's possible – indeed, vital – to be entrepreneurial, while still being true to your values. In other words, you can become an entrepreneur, but you don't have to stop being a physicist.

Jamie Ballin
London, UK

Father figure

In response to the news story about the death of Anthony Leggett, who shared the 2003 Nobel Prize in Physics for his work on superfluidity (April p4).

Your article reminds us that Leggett's first undergraduate degree at the University of Oxford was in classics and philosophy, graduating from Balliol College in 1959. But wanting a more definitive discipline than philosophy, Leggett decided he wanted to stay on at Oxford to do a second undergraduate degree in physics.

Balliol, however, hesitated whether to offer Leggett a place to read another undergraduate degree. With National Service looming, it was my father Michael Baker – physics tutor at Merton College – who stepped in to offer Leggett a scholarship at Merton to enable him to stay on, though he did go back to Balliol for tutorials in theoretical physics with David Brink.

After my father's death in 2017, Leggett wrote to me that he "was a pivotal influence in my career, indeed without his generous help and encouragement I doubt if I would ever have become a professional physicist".

Timothy M M Baker
Oxford, UK

The dark art of black holes

Fabian Oefner 2014. Inkjet print, 31½ × 47¼ in. (80 × 120 cm). Courtesy of the artist

Black Hole, no. 2
Fabian Oefner made this image of gas swirling around a black hole by putting liquid paint on a drill bit and letting the paint spray out by centrifugal force while photographing it with a high-speed camera.

Tushna Commissariat talks to author and historian **Lynn Gamwell** about her fascination with abstract art, visualizing the invisible, and how science and art interact – and introduces an edited excerpt from Gamwell's new book *Conjuring the Void: the Art of Black Holes*

Black holes, as their name suggests, are veiled in darkness and mystery. These brooding celestial behemoths are regions of space–time that consume not just stellar dust and light but the attention of astronomers, artists and non-scientists too. Often depicted as shadowy maws ringed by fire, these inescapable pits intrigue us all.

"Science has produced a wealth of information about black holes that has been popularized worldwide," says author, curator and art historian Lynn Gamwell. "This has prompted artists to delve deep into their creative imaginations to find the significance of black holes within a broad cultural context."

Unable to escape from the lure of black holes herself, Gamwell – who teaches the history of art, science and mathematics at the School of Visual Arts in New York – has written and compiled *Conjuring the Void: the Art of Black Holes*. The stunning coffee-table book is a definitive – and near-exhaustive – collection of black-hole art, including 155 colour illustrations, perfectly mixed with information about the science and history of these objects.

Readers will undoubtedly fall into the pull of the book's gravity, in which Gamwell skilfully weaves together our scientific understanding of black holes along with interpretations of these regions of space–time by artists around the world. Indeed, the book uses every medium available to decipher these objects.

With a background in the arts and humanities, Gamwell's interest in science came while studying modern art. "The explanations of abstract, non-objective art that were taught to me never made sense," she says. "While it seems so obvious now, I finally figured out that artists express their worldview and the modern worldview is shaped by science, which discovered invisible forces – such as electromagnetism – that can't be pictured."

Gamwell's previous books – *Mathematics and Art* (2015) and *Exploring the Invisible* (2020) – both focused on the more abstract aspects of maths and science that are often complex and difficult to visualize. A few years ago, she was invited by physicist Peter Galison, director of Harvard University's Black Hole Initiative (BHI), to give a talk at its annual conference.

"In researching for the talk, I was amazed to learn how many artists had done art about black holes," Gamwell recalls. "So I decided to write a book about the artistic phenomenon and why black holes have captured the public imagination." Gamwell is now an affiliate of the BHI, which brings together scientists, mathematicians and philosophers of science to deepen our understanding of black holes.

Given the interdisciplinary nature of her work, Gamwell regularly meets artists interested in science as well as scientists interested in art, including the Event Horizon Telescope's Shep Doeleman, whom this book is dedicated to. "Artists and scientists arrive at similar ideas by different paths," she says. "Both benefit from looking at each other's work."

The art – and, by extension, the artists depicted in *Conjuring the Void* – shows how the human conceit of "nothingness" links us to black holes. "On the one hand, the black hole provides artists with a symbol to express the devastations and anxieties of the modern world," Gamwell writes. "On the other hand, a black hole's extreme gravity is the source of stupendous energy, and artists such as Yambe Tam invite viewers to embrace darkness as a path to transformation, awe, and wonder."

Below is an edited extract from chapter three of *Conjuring the Void*, illustrated by a selection of images of art from the book. They depict everything from colliding black holes and their gravitational waves (p23) to a black hole's accretion disc (p22) and even a sonic wormhole (p26). We hope they also take you on a journey of awe and wonder.

Lynn Gamwell does interdisciplinary research on the connections among art history, the history of mathematics and the history of science. She teaches these subjects at the School of Visual Arts in New York. **Tushna Commissariat** is a features editor of *Physics World*

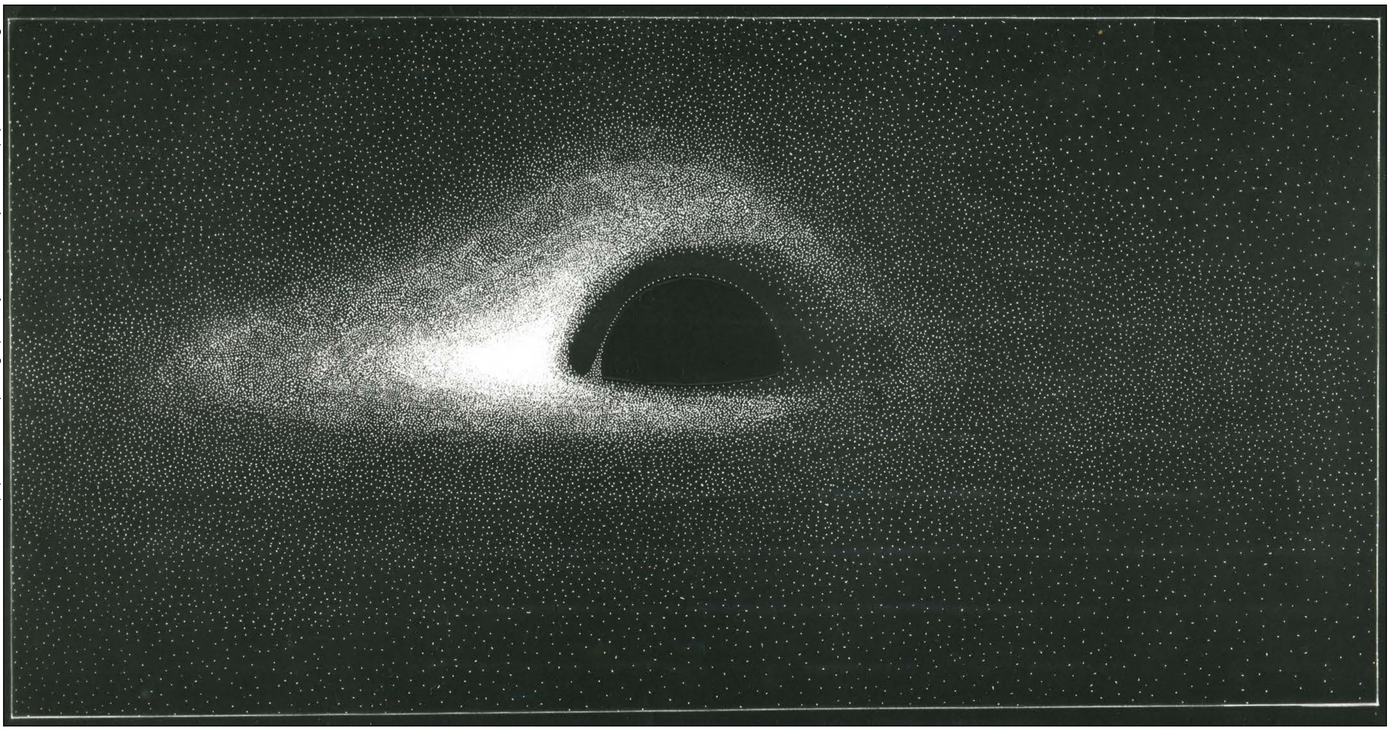
Artistic and scientific images of invisible objects

In the early 1970s the existence of black holes was reported in scientific papers and newspapers around the world, starting with the discovery of Cygnus X-1, introducing the phenomenon to the culture's imagination. Scientists symbolized data in charts, graphs and mathematical formulae and attempted to make images of black holes. But seeing an object requires light, so rather than depicting a black hole itself, scientists imagined what matter surrounding it would look like. Artists, in turn, subjected scientific data to the transformation of the imaginative process and created something completely new: artworks.

In the decades before scientists showed that black holes exist, several artists in the West –including the American Barnett Newman, the Argentine-Italian Lucio Fontana, the American Lee Bontecou, and the Englishman John Latham – made abstract art about dark voids.

As scientists were confirming the existence of black holes, Frederick Eversley was imagining sculptures of them. He graduated in 1963 from the Carnegie Institute of Technology (now Carnegie Mellon University) in Pittsburgh with a degree in engineering and worked in the aerospace industry building acoustic laboratories for NASA. Around 1970 he transitioned to being an artist,

Seeing an object requires light, so rather than depicting a black hole itself, scientists imagined what matter surrounding it would look like. Artists, in turn, subjected scientific data to the transformation of the imaginative process and created something new
Lynn Gamwell



Jean-Pierre Luminet 1979. Ink on paper, reversed photographically, in *Astronomy and Astrophysics* **75** 231, fig. 11

Spherical Black Hole with Thin Accretion Disk
One of the earliest scientific images of a black hole, this drawing shows the curvature of space–time in the vicinity of the black hole. Jean-Pierre Luminet is an astrophysicist at the Laboratoire d'Astrophysique in Marseille.

creating abstract sculptures in cast polyester. With his background in science, Eversley understood the significance of the discovery of Cygnus X-1 in 1971.

That same year, the Brazilian artist Anna Maria Maiolino began a series of artworks about her life under Brazil's military dictatorship. Whereas most artists in the early 1970s didn't pay much attention to black holes because there were no visualizations of them to fire their imaginations, Maiolino became fascinated with holes filled with darkness.

Black holes were a metaphor for resistance to political repression in the work of Rudolf Sikora – in his case, from the Communist government of Czechoslovakia. In the early 1970s he began a series called *Concentration of Energy* featuring black holes.

Early scientific images of black holes

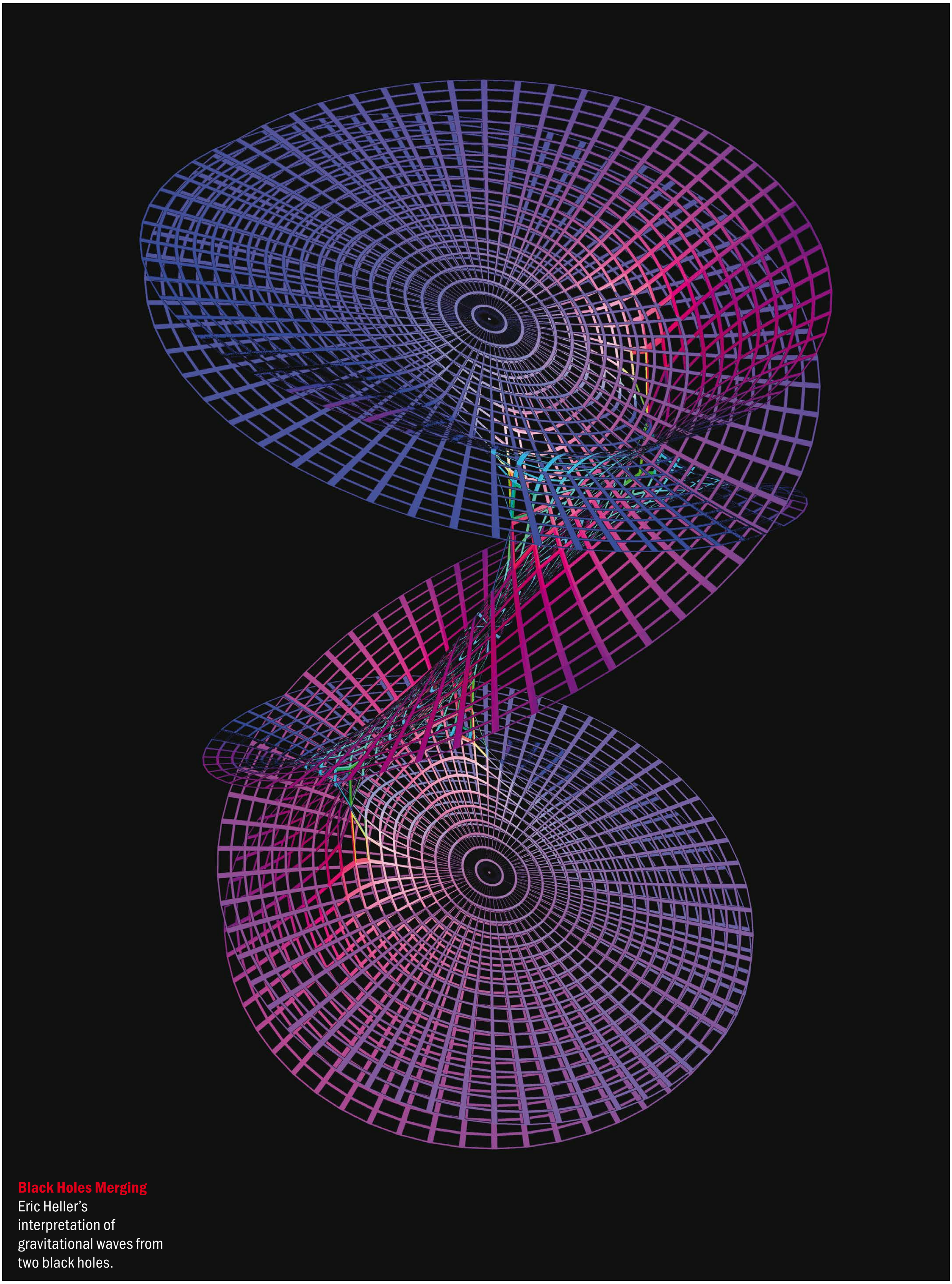
While Eversley, Maiolino and Sikora were in their studios making artworks about black holes, the US physicists C T Cunningham and James Bardeen were in their laboratory creating an illustration of the deformations in space–time around a black hole. They imagined a distant observer seeing a star orbiting a black hole at a uniform distance. They knew that the rapidly rotating black hole's gravity affects light passing through its gravitational field in a manner similar to a powerful lens, hence the observer would see light that is distorted by what astronomers call gravitational lensing. Cunningham and Bardeen calculated these optical deformations and in 1973 produced the first scientific visualization of space–time around a black hole.

What would gravitational lensing do to the cloud of dust and gas that orbits a black hole called the accretion disc? The French astrophysicist Jean-Pierre Luminet wanted to make a realistic picture of an accretion disc. Associating realism with photography, he imagined the black hole "as seen by a distant observer" taking a "photograph" from a stationary, authoritative viewpoint. In Luminet's diagram (see above), the accretion disc forms a flat, circular disc of dust and gas. Friction and magnetic forces heat the accretion disc to hundreds of billions of degrees until it becomes an incandescent plasma emitting radiation. The observer looks down on the disc from a slightly elevated position (at a 10-degree angle, labelled "observer's direction"). While the accretion disc and stars emit light in all directions, for simplicity's sake Luminet imagined parallel light rays coming from the observer's direction.

Luminet made his drawing with tiny dots of black ink on white paper and then photographically reversed the image so that it reads white against a black background to create a "simulated photograph" of a luminous object in the darkness of space. His drawing shows one additional optical deformation lacking in Cunningham and Bardeen's line drawing. The accretion disc displays a dramatic Doppler effect since it's rotating close to the speed of light. Light appears closer to the blue or red end of the spectrum depending on whether the source is moving toward or away from the observer. In Luminet's drawing, the disc's left side appears to be moving toward the observer, so the observed frequency (hence the energy) of the electromagnetic waves is very high. Since Luminet's image is black and white, he shows all radiation in the electromagnetic spectrum in what photographers call a bolometric photograph.

In Luminet's image, the innermost stable circular orbit is the smallest circular orbit in which matter can stably orbit the black hole; it's the inner edge of the accretion disc. If matter goes inside that orbit, it quickly falls past the black hole's event horizon. Since light has no mass, it can orbit within the innermost stable circular orbit. If light crosses the event horizon it will not escape, but some photons circle on a narrow path between the innermost stable circular orbit and the event horizon. Scientists call this structure a photon ring (some call it a photon sphere because it's three-dimensional).

Luminet published his work in 1979 and concluded with these prophetic words: "Thus our picture could represent many relatively weak sources, such as for

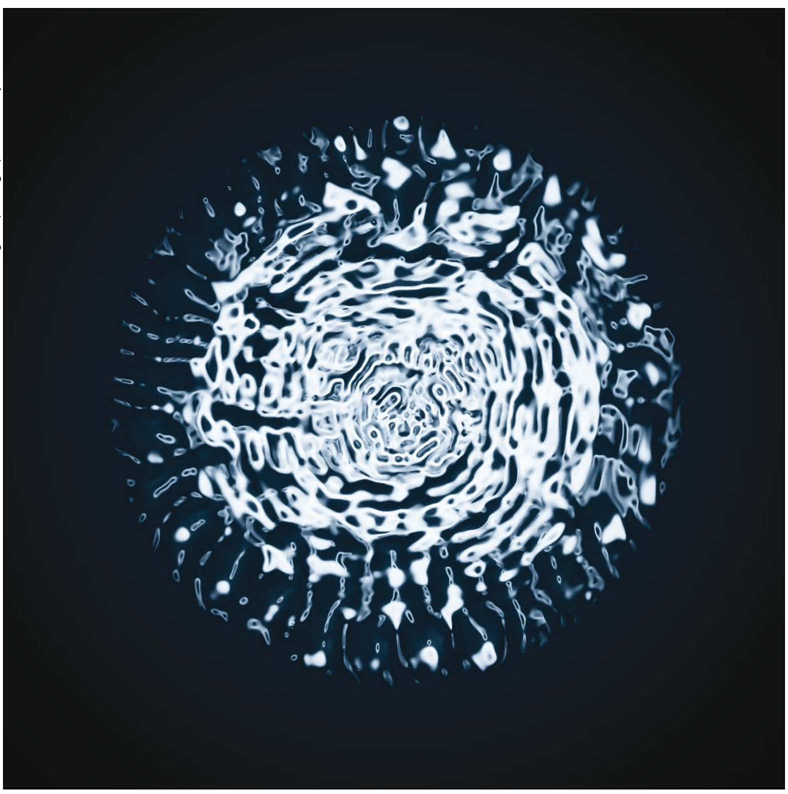


Eric Heller 2020. Digital image. Courtesy of the artist

Black Holes Merging
Eric Heller's interpretation of gravitational waves from two black holes.

Lucas J Rougeux 2021. Charcoal and acrylic on paper, 8 × 8 in. (20.3 × 20.3 cm). Courtesy of the artist

Light Particles Against a Black Hole Artist Lucas J Rougeux says: "This [work] displays the balance and ever-presence of life and death through the overlapping lenses of religion and astrophysics. Symbolic through lines [in my work] include the amorphous space cloud, the soul as recycled energy, the mysterious finality of death, and the void of black holes."



John White 2023. Digital photograph. Courtesy of the artist

Black Echo In 2022 NASA scientists detected pressure waves produced by a black hole and translated them into sound waves that humans can hear. John White photographed water vibrating in response to the sound waves – a musical note 57 octaves below middle C.

instance the supermassive black hole whose existence in the nucleus of M87 has been suggested recently." Forty years later, the black hole in the centre of galaxy M87 was imaged by the Event Horizon Telescope.

Added colour

Jean-Alain Marck – Luminet's colleague at the Paris-Meudon Observatory – was an expert in general relativity, computer programming and calculating geodesics around a black hole. A geodesic is the shortest distance between two points on a curved plane. In 1989 Marck calculated the geodesics describing the accretion disc in Luminet's drawing from various angles and, for dramatic effect, added colour. An image of a black hole from 1997 shows the far side of the accretion disc's top side and underside. Marck and Luminet's image had shown this view earlier, but it remained unpublished.

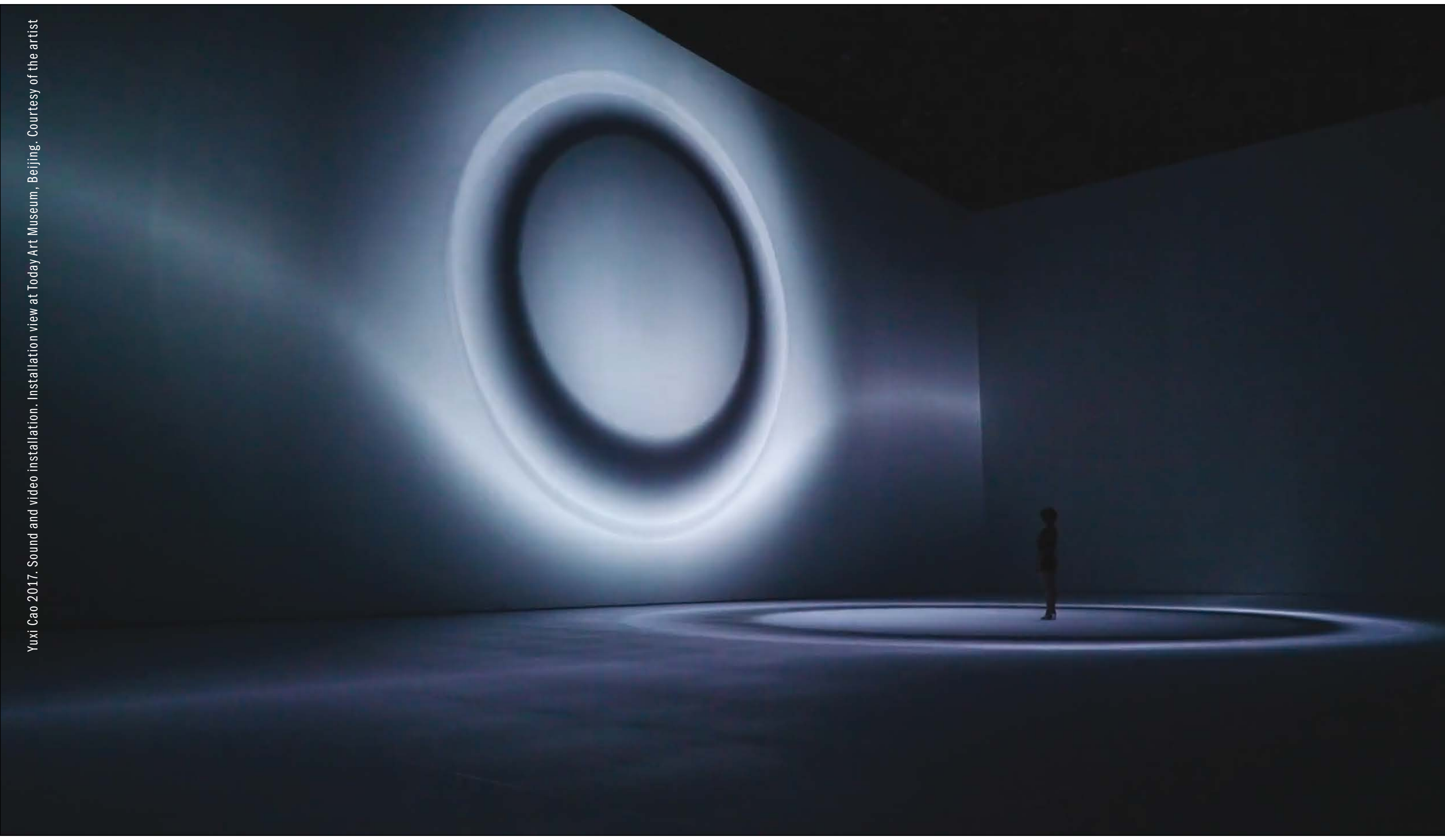
In the early 1990s Marck and Luminet collaborated on a sequence about black holes for a television documentary that was broadcast across Europe. Luminet had drawn his image by hand in the late 1970s because computer graphics programs were not available, but by the 1990s the technology had advanced and Marck was able to write the animation program himself. Marck's calculation is unusual because it shows what a moving observer – riding a magic carpet and wearing a bow in her hair – would see flying past a Schwarzschild black hole on an elliptical trajectory.

While Luminet's monochrome picture depicted the total radiation in all wavelengths, astronomers Jun Fukue and Takushi Yokoyama imagined a visible-light photograph of an accretion disc. Luminet, Fukue and Yokoyama visualized thin accretion discs around Schwarzschild (stationary) black holes and a thick accretion disc around a Kerr (rotating) black hole from an almost edge-on viewpoint. Artist Fabian Oefner created an artwork that is a metaphor for a multicoloured accretion disc, representing the visible light from a rotating black hole (see p20).

If a black hole is rotating, the speed at which it spins affects the diameter of the innermost stable circular orbit; the faster it spins, the smaller its diameter. If a Kerr black hole spins extremely fast, it will distort space–time at the inner edge of the accretion disc. A thin accretion disc around a maximally rotating Kerr black hole from an elevated viewpoint shows asymmetry of the disc's inner edge as the result of frame-dragging; the rotating black hole "drags" space–time along.

Melissa Walter created a sculpture that is a metaphor for gravitational lensing. Light passes through cut paper that sways and curves, distorting the light like a gravitational lens. Walter, unlike many artists, understands the crucial distinction between a science illustration and an artwork. Under her maiden name, Melissa Weiss, she works for NASA, executing science illustrations of how a black hole might actually appear, such as the widely used image of Cygnus X-1 and its companion star. Under her married name, Melissa Walter, she creates artworks. Speaking about the development of her oeuvre, she said: "Abstraction has been the common thread throughout that evolution as it relates to humanity's place in the cosmos."

Eric Heller is a physicist who studies wave phenomena in quantum mechanics, acoustics and oceanography. He's also a practising artist who creates digital images



Yuxi Cao 2017. Sound and video installation. Installation view at Today Art Museum, Beijing. Courtesy of the artist

Oriens: Immersive Black Hole
Yuxi Cao (James Cao) created this installation where the viewer can walk around in the video projection of a black hole.

about scientific subjects. In *Black Holes Merging* (see p23) he imagined the pattern two black holes might make when they spiral into each other.

The popularization of black holes

In the late 1970s popular-science books about black holes began appearing, including Isaac Asimov's *The Collapsing Universe: the Story of Black Holes* (1977). Having earned a PhD in chemistry, Asimov drew on a deep knowledge of science and was a skilled storyteller. Another title that contributed to the popular fascination with black holes was Stephen Hawking's *A Brief History of Time: From the Big Bang to Black Holes* (1988) and the 1991 film based on it. Inspired by the words of Hawking, the Italian art collective Opiemme painted letterforms surrounding a long shape that symbolizes an event horizon.

Carl Sagan's book *Cosmos* (1980) sold five million copies internationally. The related TV series, *Cosmos: a Personal Voyage* (1980), was hosted by Sagan and shown in 60 countries to 400 million viewers. A sequel, *Cosmos: a Space–time Odyssey* (2014), hosted by Neil deGrasse Tyson, was shown in 125 countries to 135 million viewers. Sagan and Tyson described many scientific topics, including black holes, which were brought to life by animators.

The impact of these popularizations was felt around the world, and artists in Asia mixed Western science with Eastern philosophy and history. Cai Guo-Qiang was in his 20s when he began experimenting with gunpowder as an artistic medium. When you explode a small amount of gunpowder on paper, it leaves a mark. Cai called these works "gunpowder drawings". In 1986, at age 29, he moved from his native China to Japan and became enthralled by popular books about astrophysics, especially *A Brief History of Time* and *Cosmos*, which he read in translation.

Cai said: "When I came to Japan, my encounters with the theories of 20th-century astrophysics were very significant to me. The concepts of the Big Bang, black holes, the birth of stars, what is beyond the universe, time tunnels, how to leap over great distances of time and space and dialogue with something infinitely far away – these ideas were still not commonly in circulation in China at the time. They were an eye-opener for me. At the same time, many of these ideas have similarities with traditional Chinese views, with which I was familiar, of metaphysics and the universe."

In 1991 Cai created large gunpowder drawings on paper mounted on wood panels, such as *The Vague Border at the Edge of Time/Space Project*. Then he joined the wooden panels together, transforming them into traditional Chinese folding screens. He called the series *Primeval Fireball: the Project for Projects* because his drawings, like the cosmos, exploded into existence.

Lucas J Rougeux was inspired when in 2014 astronomers watched as what appeared to be a cloud of dust (G2) approached Sagittarius A*. They expected the space cloud to be sucked into the black hole, but it survived the encounter. (Astronomers now believe that G2 was a binary star system that orbited the black hole in tandem, eventually merging into an extremely large star.) After learning about G2, Rougeux created a series of artworks about black holes (see opposite) that were shown in a 2022 exhibition titled *The Soul Gravity—Guided to Black*. The artist said, "The delicacy and amorphous nature of a space cloud is directly

Wormhole Bell Yambe Tam's sculpture of a wormhole has feedback microphones that turn it into a bell.

Yambe Tam 2018. Cast bronze, 11¾ × 11¾ × 14 in. (30 × 30 × 36 cm). Private collection. Photo: Albert Barbu

> To me, black holes and the speculative, double-ended form of the wormhole are symbols of transformation – whether the breakdown of classical Newtonian physics to general relativity or the spiritual transcendence one feels in contemplative practices like zazen
>
> Yambe Tam

connected to my own sense of queer identity…I am a cloud of space dust. I am a collection of particles dealing with depression. I am weaving through waves of space–time and isolation. My work is the product of this existentialism, loneliness and search for a connection to the sublime."

In 2022 NASA released a new sonification of the black hole at the centre of the Perseus galaxy cluster, which inspired the photographer John White. He painted the bottom of a petri dish black, filled it with water, and set it on top of a speaker. As he played the sound of the black hole through the speaker, the water began to vibrate. Shooting directly down at the petri dish with a macro lens and a halo light in a darkened room, he captured the vibration in a photograph titled *Black Echo* (see p24).

Immersive art about black holes

Artists create immersive art – artworks the viewer can walk into – to enhance the immediacy of the experience. In 2016 the choreographer Wen-chi Su was an artist-in-residence at CERN, where she met the theoretical physicist Diego Blas, and they discussed the meaning of gravity in dance and astronomy. Su imagined what happens when a body falls into a black hole. Together with her production team, she directed a film in which the sets were animations and the movements of the dancer were captured by motion sensors. Additionally, a surround-sound system immersed the audience in a three-dimensional sound field.

Cao Yuxi (James Cao) is a computer artist who created an artwork about a black hole that he titled *Oriens* (Latin for "Orient"), giving it the subtitle *Immersive Black Hole* because the viewer is able to walk around in the space of the artwork (see p25). His projection of a sphere on the wall suggests a black hole. A circle symbolizing the event horizon is projected on the floor, and flashing, curving lights communicate distortions in space–time near the black hole.

The American artist Yambe Tam, who merges Western science with Chinese philosophy, has said: "Black holes are a reoccurring theme in my practice. Beyond my interest in theoretical physics, I see connections to the Buddhist philosophical concept of the void/emptiness/nothingness, which is shared more widely with other Eastern spiritual traditions. Rather than signifying a negative space or absence of something, void/emptiness/nothingness is a space of infinite potentiality. It is during the practice of zazen [silent meditation] that I most feel an embodied sense of this – the emptying of oneself, or dissolution of form and ego into pure being."

Tam's *Cosmic Garden* was created to resemble a Buddhist dry garden. From the ceiling hang several of the artist's sculptures that take the form of bells. One of these sculptures, *Wormhole Bell* (see above) has feedback microphones that turn the object into a self-resonating instrument, which helps induce a deep state of meditation. In astronomy, a wormhole is a hypothetical tunnel that connects separate regions of space–time. Tam says: "To me, black holes and the speculative, double-ended form of the wormhole are symbols of transformation – whether the breakdown of classical Newtonian physics to general relativity or the spiritual transcendence one feels in contemplative practices like zazen. Physically, travelling into a black hole is obliteration – a return to pure atomic matter. However, in more philosophical and spiritual terms, a wormhole is an unknowable space of no return, a portal to another side of reality." ■

● This is an edited excerpt from Lynn Gamwell's book *Conjuring the Void: the Art of Black Holes* (2025 MIT Press 208pp £41 hb). Reproduced with permission,

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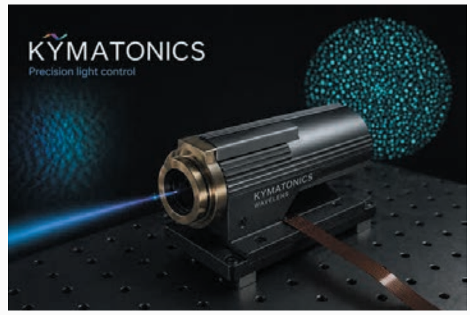

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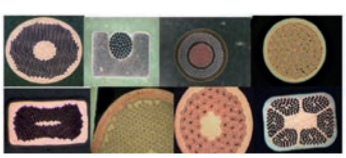

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What can we do about space junk?

Modern life depends on space-based infrastructure, but there's a lot of junk orbiting alongside working spacecraft. **Katherine Courtney** and **Alice Gorman** talk to Margaret Harris about the danger of space debris – and what we need to do about it

Katherine Courtney is chair of the Global Network on Sustainability in Space (GNOSIS), UK; **Alice Gorman** is associate professor of space archaeology at Flinders University, Australia; **Margaret Harris** is an online editor of *Physics World*

Among the working satellites and telescopes orbiting our planet is a lot of rubbish. From full satellites that no longer work to tiny bolts shed as spacecraft release spent rockets, there are millions of human-made pieces of debris in the space around Earth.

The problem is a hot topic within the space community. The presence of space junk has implications for both ground and space-based astronomy; there is an impact on atmospheric science that we're only just beginning to understand; and it also presents a threat to our highly space-reliant society.

To highlight what is being – and needs to be – done to tackle the issue of space junk, experts Katherine Courtney and Alice Gorman talked to *Physics World* online editor Margaret Harris as part of a Physics World Live panel discussion in November 2025.

Courtney started her career developing products and services for the telecoms industry before moving to the public sector and working in the UK government. While she was the chief executive of the UK Space Agency she came to realize the impact of space debris.

Courtney is now chair of the Global Network on Sustainability in Space (GNOSIS), which has about 1000 members from research and industry across more than 45 countries. GNOSIS aims to accelerate research and development efforts to tackle problems like space debris. Courtney also mentors start-up companies that are trying to solve these problems and does outreach with young people to educate them on the topic.

Gorman studied archaeology and for several years worked on terrestrial projects before becoming a space archaeologist. Now at Flinders University, Australia, she is known as Dr Space Junk, and focuses not just on debris in Earth orbit, but also planetary landing sites,

NASA

Jettisoned junk
A pallet of old batteries released into space from the International Space Station when it was 425 km above the north coast of Chile. The pallet will orbit Earth for two to four years before burning up in the atmosphere.

deep space probes, terrestrial rocket launch sites and tracking stations.

Gorman's research into space junk involves looking at objects in an environmental context, examining their cultural value and what it means to retain these objects. Along with Justin Walsh, she trained crew on the International Space Station to do what was effectively the first archaeological field survey outside Earth.

What is space junk and how much is there in orbit around Earth?

Alice Gorman: Space junk is commonly defined as any object in space that does not now or in the foreseeable future serve a useful purpose. The biggest contributors to the space debris population are the US, Russia and China.

The latest figures estimate that there are 54 000 human-made objects in orbit that are larger than 10 cm, including over 14 000 operating satellites and spacecraft. Envisat is one of the largest in that category, being 26 m long. There are also medium-size objects, which can be anything from 1 to 10 cm. Current statistical models estimate there are about 1.2 million objects of this size. At an even smaller scale, there's an estimated 140 million objects 1 mm to 1 cm in size.

Not all these objects are tracked and catalogued – the number regularly tracked by Space Surveillance Networks is only about 44 870. But that doesn't mean that's everything there is – that's just the things we can see and know are there.

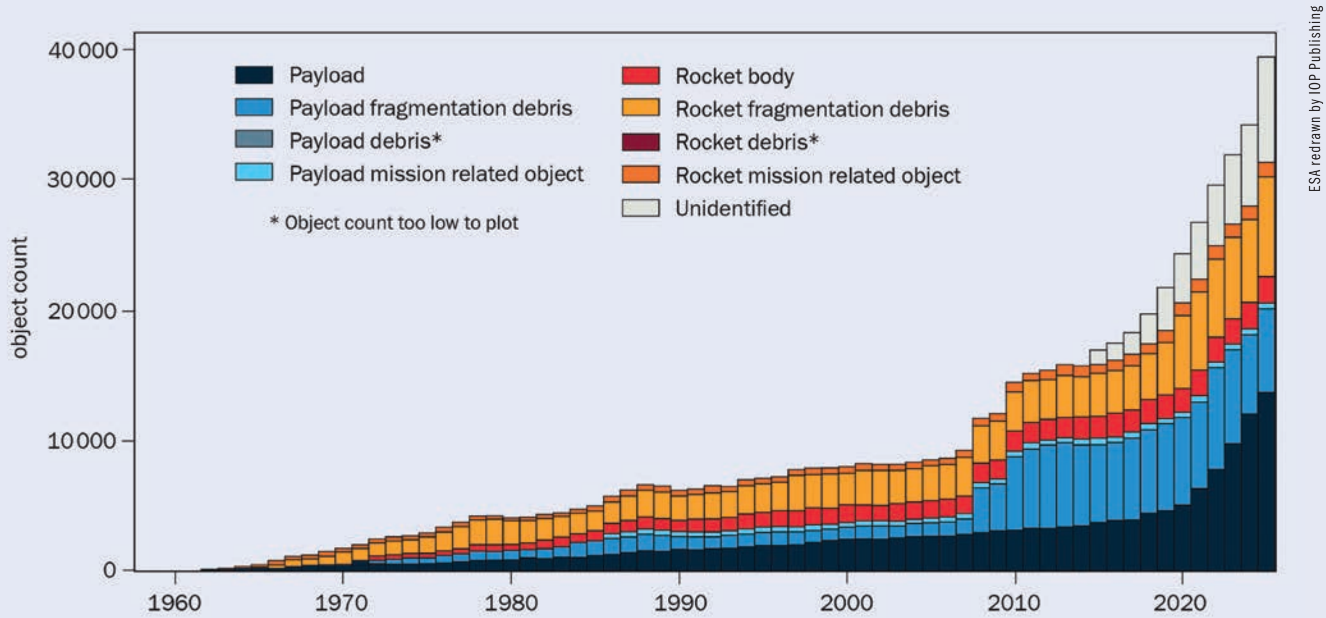
What sorts of objects make up space junk?

Alice Gorman: First, there are whole satellites that no longer work. There are the upper stage rocket bodies that are left in orbit after they've delivered their payload – and in some cases are still attached. There are bolts, lens caps, fuel tanks – all kinds of debris that are released into orbit as part of a spacecraft's mission or satellite launch.

Then you have the hundreds and thousands of fragments from exploded spacecraft. There have also been a number of anti-satellite tests that have added to the debris population. One notorious example was when China destroyed its own Fengyun-1C satellite using a missile in 2007. The event created around 3500 trackable objects and many more smaller pieces of debris, a lot of which are still in orbit.

There are also all the tiny fragments resulting from

Taking up space



The count evolution of different types of human-made debris in geocentric orbit, as recorded by the European Space Agency:

- **Payload** – an object designed to perform a specific function in space (excluding launch functionality). This includes operational satellites as well as calibration objects.
- **Payload fragmentation debris** – an object that has fragmented or unintentionally released from a payload as space debris with origins that can be traced back to a unique event. This class includes objects created when a payload explodes or when it collides with another object.
- **Payload debris** – an object that has fragmented or unintentionally released from a payload as space debris for an unknown reason but orbital or physical properties allow it to be traced to a source.
- **Payload mission related object** – an object that served a purpose for the payload and has intentionally been released as space debris. Common examples include covers for optical instruments or astronaut tools.
- **Rocket body** – an object designed to perform launch-related functionality. This includes the various orbital stages of launch vehicles, but not payloads which release smaller payloads themselves.
- **Rocket fragmentation debris** – an object that has fragmented or unintentionally released from a rocket body as space debris with origins that can be traced back to a unique event. This class includes objects created when a launch vehicle explodes.
- **Rocket debris** – an object that has fragmented or unintentionally released from a rocket body as space debris for an unknown reason but orbital or physical properties allow it to be traced to a source.
- **Rocket mission related object** – an object intentionally released as space debris that served a purpose for the function of a rocket body. Common examples include shrouds and engines.
- **Unidentified** – an object that has not been traced back to a launch event.

debris being continually bombarded by micrometeoroids and other bits of space junk. Plus, materials decay and erode when they're in space.

Where is all this space debris?

Alice Gorman: The most congested area is low-Earth orbit – about 200 to 2000 km above sea level. Among the working satellites in this orbit are around 9000 that are part of SpaceX's Starlink network.

Medium-Earth orbit (between roughly 2000 and 35 000 km) has a lot of stuff in it but also contains the Van Allen radiation belts so tends to be avoided. Then we get to geosynchronous and geostationary orbit at 35 786 km, where a lot of telecoms satellites are. Finally, beyond that is the graveyard orbit, where geostationary satellites that no longer work are sometimes boosted up to.

What hazards do these human-made objects pose to the space environment?

Katherine Courtney: First you have to consider just how dependent we are on the infrastructure that is orbiting the planet. The Internet, mobile telephones, banking networks, utility grids, emergency services, food distribution, climate change monitoring, stock markets – all of these things and so many more depend on space.

In 1978 American astrophysicist Donald Kessler proposed that if certain orbits get too congested with debris and active satellites, there could be a collision that triggers a chain reaction of further collisions, making those areas of space unusable for generations. It's what's known as the Kessler Syndrome.

Kessler and UK astronautics engineer Hugh Lewis recently released an update to that original paper. Using European Space Agency (ESA) data on space debris, they determined that Kessler Syndrome is actually already happening at some orbits, and there are a whole range of other orbits that are now considered unstable and potentially at risk.

We don't know for sure that we're at that catastrophe scenario where the orbits become too congested with objects that can't be controlled by humans. But the modelling suggests we are well on our way to that situation.

ZUMA Press Wire/Shutterstock

Close encounters Local residents finding debris from the first stage of a Long March-3C carrier rocket in Jiulongshan Village, Shibing County, Guizhou Province, China, in November 2010.

Even tiny debris can make a satellite inoperable. Satellites often just stop working, and nobody knows if that's because they've had a debris strike, an electrical malfunction or some other fault. In ESA's latest annual report on the debris population, they say that even if no further launches occur, the debris population will continue to expand because of the decay and fragmentation of those legacy rocket bodies and big defunct objects that we have no way of retrieving, reusing or controlling.

Debris isn't the only hazard. There's quite a complex system up there where hazards are impacting each other. Some orbits are now getting so congested that it's getting very difficult for operators to avoid collisions, and they are having to manoeuvre satellites daily to avoid them. Starlink publishes their collision manoeuvre statistics and – when you plot it – you can see how it's going up and up as they increase the size of their constellation.

But debris doesn't advertise where it is. As Alice described, we only have a certain number of trackable objects – the other million plus are not trackable. So there's an interplay between how crowded inoperable things are and how crowded manoeuvrable things are.

What impact does space weather have on debris?

Katherine Courtney: Every time we see an aurora in the night sky, it might look pretty but it means that the satellites in orbit around the Earth are being washed with some serious magnetic particles from the Sun. Along with the risk that a massive solar storm could knock out satellites if it was blasted in Earth's direction, the influx of these particles increases the atmospheric drag and moves the debris in unpredictable ways. Space weather interacts with both active satellites and debris in a way that increases the uncertainties about just how many things we can safely operate up there.

This is also becoming more hazardous because constellation operators in low-Earth orbit have started to introduce artificial intelligence and automated manoeuvring systems. They've done that because if you have 9000 satellites, you can't employ (or don't want to employ) 9000 people to operate them from the ground. So they have all developed automated station keeping, which is a good idea if the idea is to keep the satellite in place.

But there isn't really a system in place whereby operators announce in advance these automated manoeuvres. Yes, they will try and contact other operators on a sort of "best efforts" basis if they are going to do planned manoeuvres, but unplanned ones are a whole new hazard.

What impact can space junk have on astronomy?

Katherine Courtney: Space junk is quite a challenge for astronomers. They have facilities that have taken 10 years to build and cost billions, but they are getting streaks in their imagery and they are losing data points. It's a real challenge to deal with that because when these telescopes were designed, we didn't have 13 000 satellites flying around and more than 10 000 of them moving fast in low-Earth orbit.

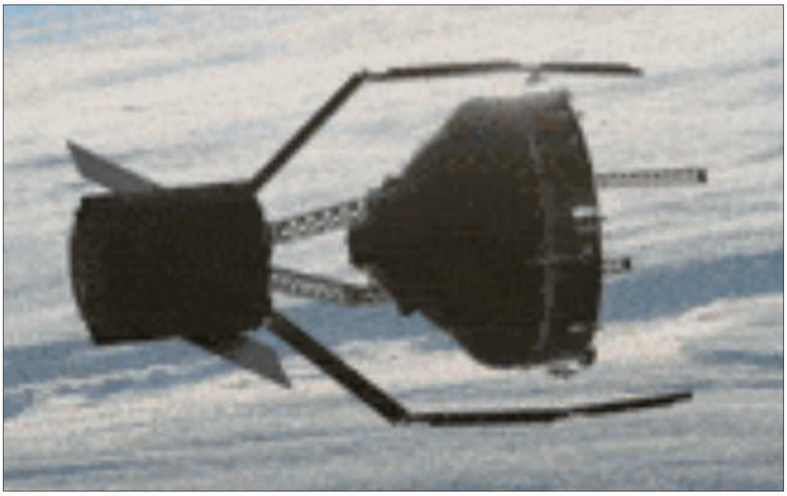
Radio astronomy is also being interfered with because satellites are transmitting signals all the time. There is some evidence they are also leaking unintentional emissions from their electrical systems, which – again – interferes with astronomy.

And what impact does space debris have on the environment?

Katherine Courtney: There is emerging evidence that when debris re-enters the Earth's atmosphere, it deposits particulate matter into the atmosphere that we have never experienced before. Naturally occurring matter from meteorites and micrometeorites don't carry the metals we've extracted from Earth and launched into space, which are now burning up on their way back down.

And not all objects burn up. You can find some quite

ESA



Cosmic litter-picker The European Space Agency is preparing for active debris removal missions and design for removal (D4R) technologies that can be used to ensure the safe disposal of satellites that are unable to move on their own at their end-of-life.

scary pictures of very large things that have landed on Earth – thankfully not on anybody's head as far as we know. They usually land in places like Australia, a long way from inhabited areas, or in the middle of the Pacific Ocean – but they're not being controlled as they descend.

A couple of years ago, a Chinese Long March rocket body re-entered the atmosphere uncontrolled. If it had arrived 15 minutes earlier, it would have landed on New York City. All you can do is cross your fingers and hope that when objects come down, they're not landing on a bunch of people somewhere.

What is being done – or could be done in the future – to reduce the hazards of space junk?

Alice Gorman: This is an urgent problem that we need action on. At the moment, there are many proposals and missions in testing or development to actively remove debris from orbit, but none are actually working. For new missions, however, there has been a really interesting shift.

We used to look on the atmosphere as a natural incinerator, and all the plans to get rid of stuff in orbit involved tipping them back into the atmosphere to mostly burn up. It was considered to be the logical and most harmless way to dispose of space junk. But objects don't always burn up, and stuff still makes it to the ground.

We also now know that these aluminium and soot particulates [created by objects burning up] in the upper atmosphere are affecting the ozone layer. We thought we had solved that problem with the 1987 Montreal Protocol, when the world came together to stop the ozone layer being destroyed.

People now realize you can't just let satellites burn up. In fact, there are now proposals, like ESA's Zero Debris Charter, for new missions to not create any new debris – to be "debris neutral". That's great for current and future missions but are people actually going to do it?

There used to be a rule – don't leave anything in orbit for 25 years and have an end-of-life strategy to get rid of it. That's now down to five years, which is good. But apparently only 40 to 60% of satellite operators followed that protocol – the rest would simply do nothing to prevent their spacecraft from contributing to the debris problem.

We rely on satellite operators and launch operators complying with these international standards and norms. And when profit is at stake, I don't think we can have any guarantee that they will actually do that.

Katherine Courtney: When I first began focusing on space debris, I sometimes felt there were just the United Nations (UN) long-term sustainability guidelines. They were voluntary, but people are now bringing that into their national space law. There is increasing awareness of the issue and satellite operators are beginning to engage in those conversations differently.

ESA's Zero Debris Charter is a great initiative because it sets timed targets and detailed technical specifications for how not to create additional debris with your missions. Unfortunately, it still calls for five-year design-for-demise as best practice, which maybe isn't the answer. Missions should be designed for reuse and recycling. Or we need to not only not create debris, but use new materials that have less impact when they re-enter the atmosphere.

The International Telecommunication Union (ITU) [the UN agency for digital technologies] are really the only multilateral body that have any sort of binding powers. They allocate global radio spectrum and satellite orbits to ensure telecommunication operations run smoothly. They have started holding an annual sustainability conference where they get ITU delegates together to talk about how to fix the problem of space debris.

In 2025 the UN's Committee on the Peaceful Uses of Outer Space (COPUOS) also set up the Expert Group on Space Situational Awareness – under the Working Group on the Long-term Sustainability of Outer Space Activities (LTS) – because one of the real problems is that we don't have a clear enough picture of what is going on in orbit.

As Alice described, we can't see the vast majority of the debris, but we also collect the data about debris through lots of non-standardized observations that are not interoperable and are made by different space agencies around the world. There are competing models that give different estimates and different forecasts.

We need to come up with a standardized way of monitoring the space environment and modelling what impact increasing numbers of spacecraft is having, so it's great to hear that COPUOS has decided to encourage that.

There is also hope from the UN's Summit of the Future in 2024. Action 56 in the resulting Pact for the Future proposes a fourth UN Conference on the Peaceful Exploration of Outer Space (UNISPACE IV) in 2027. It will focus on debris, debris mitigation and management, space traffic management, and how the world can cooperate more effectively in this area.

So what do we need to make these initiatives work?

Katherine Courtney: We currently don't have an international treaty with binding rules. Different countries require different things of their licensed operators, don't necessarily keep other countries informed of their activities, and some space objects don't even go into the intended orbits at all. We need something like the ITU – a non-military, cross-border independent authority – that could monitor and enforce standards internationally.

A little ray of light for me is that NASA recently received an e-mail from the Chinese National Space Administration to warn them of a potential collision between a

Chinese object and a NASA mission. It was the first time that had happened. Communicating to avoid collisions should be the bare minimum to ensure a more sustainable space environment.

What missions and tests have happened or are in the pipeline to deal with individual pieces of debris?

Katherine Courtney: The most advanced to date has been Japan's Astroscale ADRAS-J mission, which has demonstrated its ability to safely approach a target object and examine it closely. Meanwhile, ESA is launching its ClearSpace-1 mission in 2029 to clear an old PROBA-1 satellite from low-Earth orbit.

These missions are tricky because the first rule is don't make any more debris – but you have an object that is tumbling, maybe fragmenting and could be carrying fuel. You have to be very careful to prove that you have the technology that can safely capture that object. For ClearSpace-1, they are going to use a sort of robotic grappling mechanism (see photo, p32), while Astroscale will use a magnetic solution to grab things.

The UK government has also announced further funding to not just remove one UK licensed object from orbit, but go back and remove a second. This is quite a technical feat – you have to safely take an uncooperative debris object, lower it to a point where Earth's gravity will cause it to deorbit, and then go back and get another one, all without bumping into anything on the way.

China and Russia have also demonstrated their ability to safely approach objects but they haven't published the outcomes of those missions. China's efforts have been defence-focused but they have also started to look at commercial operations in that area. In fact, there are quite a few companies now really interested in being involved in this space.

How long might it take before the orbits get so crowded that we really just can't put anything else into orbits?

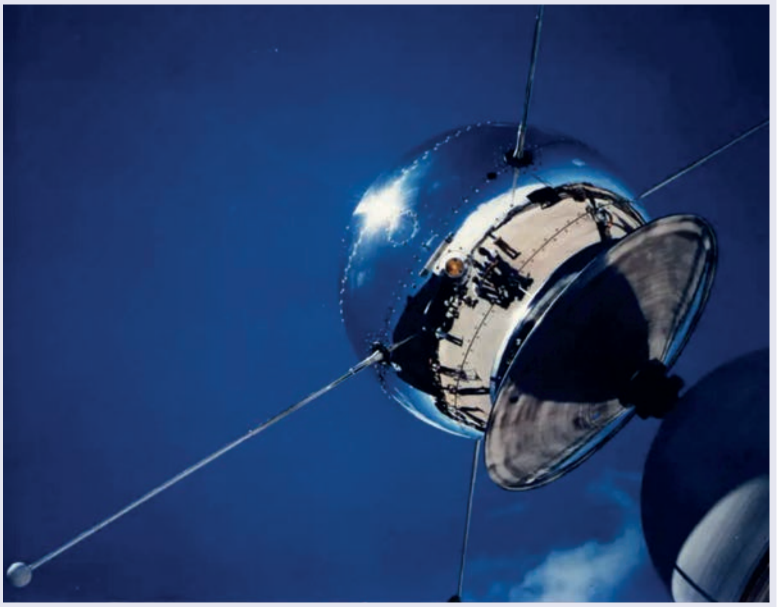
Katherine Courtney: I've not seen a forecast on how long this will take, but currently people are launching satellites weekly and in batches. According to ITU filings, there are over a million permissions to operate in certain spectrum on file now. So, over the next 10 years, a million more satellites could theoretically be launched, which could be problematic.

Imagine a motorway where everybody can drive at whatever speed they want with no indicator lights. If your car broke down and you just left it in the middle of the road, that would soon become an unusable environment. Space orbits could soon be like that.

But we can use orbital capacity more efficiently. It's just that it requires a great force of global collaboration to solve that problem because space, by definition, is a place without national borders.

My view is that 90% of space activity today is commercial. Businesses have to manage these hazards and risks or else they will close down. In fact, I see a day where something happens that makes everybody sit up. I call it the *Exxon Valdez* moment, a disaster that is small enough to hurt some operators financially, but not big enough that we have a Kessler syndrome and we all have to wait 200 years before we can use that space again. I think that's when the economic incentives will be there for people to actually start collaborating.

Do some craft have heritage value?



NASA

A shining example Vanguard 1, the world's first solar-powered satellite, launched on 17 March 1958. It was the second US satellite in orbit, following Explorer 1, and remains the oldest artificial object orbiting Earth to this day.

Alice Gorman: There have been proposals to test some debris removal technologies on older spacecraft on the basis that they might one day be a risk and they're old so nobody cares. But to me many such craft have incredible heritage value.

People sometimes say to me, "But Alice, we can't leave them there, they're junk". However, if they're not currently collision risks, we don't have to do anything about them. Instead we can assess their cultural heritage value. We can rank the objects so we can say, if something has to be removed, this object has a lower value than this one.

So, from my perspective, every nation needs to have a look at its heritage assets in orbit, assess their significance, and from that point decide what needs to be done. And in heritage terms you don't do anything until you need to – the place where something is, is an important part of its cultural significance.

You could argue that the definition of space junk is something which has no use, but these objects actually do have a purpose. Their purpose is to connect people to their history in space and to space as a place. I want to see all proposals for active debris removal incorporate cultural heritage management.

Five years ago you never heard an operator say regulation was a good thing – I now regularly attend events where operators ask for regulation. So I think we can solve these problems.

Are there any alternative approaches to avoid more space debris?

Alice Gorman: Although we depend on space, we are in fact neglecting terrestrial infrastructure. The Starlink satellites, for example, have been strongly pushed in because they promise to provide communication to remote places – but only because there has been no investment in terrestrial infrastructure. We can choose to pull some functions back from space. We're not completely committed to space for all these functions, and we shouldn't be so dependent on space.

- This article is based on the 10 November 2025 Physics World Live event, which you can watch on demand at physicsworld.com/physics-world-live

From the blackboard to the backbenches

Dave Robertson spent almost a decade as a school physics teacher before moving into politics. He tells **Matin Durrani** what it's like being a Member of Parliament – and what he's doing to support science and technology

© House of Commons/Roger Harris

Physicists who go into politics are a rare breed. Most famously there was Angela Merkel, who was chancellor of Germany for 16 years. Climate physicist Claudia Sheinbaum Pardo was elected Mexican president in a landslide win in 2024. Alok Sharma, meanwhile, was business secretary in the UK government and president of the COP-26 climate summit.

But Dave Robertson is even more unusual. Having originally studied physics at the University of Liverpool in the UK, he worked as a physics teacher in Birmingham for almost a decade. After spells in the trade-union movement and local politics, Robertson has been the Labour Member of Parliament (MP) for Lichfield, Burntwood and the Villages since 2024.

He's not the only physicist currently serving as an MP. Others include Layla Moran – another former physics teacher – who's been Liberal Democrat MP for Oxford West and Abingdon since 2017. There's also shadow home secretary Chris Philp, who's been Conservative MP for Croydon South since 2015.

But Robertson is the only physics-teacher-turned-MP in the current Labour government, which came to power at the 2024 general election. It won a 174-seat landslide majority, though Robertson's own victory was wafer-thin. He squeaked home by just 810 votes over his Conservative rival Michael Fabricant, who had been Lichfield's MP for more than 25 years.

In an interview with *Physics World*, Robertson admits he had little idea of what the job of MP would involve (see box on p36). Describing the British parliament as "a truly bonkers and bizarre workplace", he divides his time between Lichfield and London. "I try to do four days in my constituency a week and four days in parliament. That doesn't add up, but if can split my Mondays, I can just about make it work."

Into the classroom

Brought up in Lichfield, Robertson began his physics degree at Liverpool in 2004. Saying he "loved every second" of his time there, Robertson particularly enjoyed nuclear physics. But it was a science-communication course, which Robertson admits he only took because he thought it would be easy marks, that made him realize how much he liked taking complicated concepts and explaining them to non-experts.

After graduating in 2007 and taking a year off, Robertson returned to the Midlands to do a teacher-training degree at the University of Birmingham. The course was largely practical, with Robertson spending most of his time getting hands-on teaching experience at various schools in Birmingham, including one – Great Barr School – that he ended up working at.

Robertson spent seven years as a physics teacher at Great Barr, which was then one of the largest secondary schools in the UK. With about 2500 pupils, it had as

Matin Durrani is editor-in-chief of *Physics World*

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Heart of the country Dave Robertson was elected as Labour Member of Parliament for the Staffordshire seat of Lichfield, Burntwood and the Villages at the 2024 UK general election, beating the sitting Conservative MP Michael Fabricant by just 810 votes. The former physics teacher serves a semi-rural constituency centred on the cathedral city of Lichfield (pictured). Lying about 30 km north of Birmingham, the constituency also includes farmland, villages and the town of Burntwood.

Dave Robertson MP: after I got elected

Dave Robertson recalls the immediate aftermath of his victory in the UK general election on Thursday 4 July 2024

When you win an election, they give you this envelope. I was expecting a proper, thick A4 envelope, but all they gave me was a single sheet of A4 paper folded in half. It was 4.30 in the morning, I'd had no sleep and I'd been on my feet since 7 a.m. or something stupid. And I thought "I'm not opening this now. I'm going to take it home."

When I opened it in the morning, it basically said "Congratulations, phone this number." So I rang and someone said "Oh, when are you coming down to parliament?" And my reaction was "I thought you'd tell me that!" In the end, I went down on the Sunday after the election and I remember walking into Westminster Hall for the first time with the person who was showing me round and she said, "So when was the last time you were in parliament?"

As I put my hand on the door, I had to admit I'd never been in the building before: it was literally the first time I'd ever been there. And it's nothing like I expected. It is a truly bonkers and truly bizarre workplace. It's unique and so different to everything else. That comes with its frustrations, but it is also an absolute privilege to be involved – and long may it continue.

many as 16 classes in each year group, from age 11 to 16. Great Barr was also able to offer physics to 17 and 18 year olds who stayed on to do A-levels. "We'd always have one physics group or occasionally two in year 12."

Rather than just focusing on the syllabus, Robertson would try to make his lessons "loud and engaging" to emphasize the excitement and sheer bizarreness of physics. Claiming he has good control of his voice, Robertson says he would also "put on accents and do silly voices" to keep pupils entertained.

He particularly enjoyed teaching a course called "Science in the news", where pupils would look into the impact of a particular topic in the syllabus on the wider world. "That was wonderful," Robertson recalls. "It was effectively a literature review, which let us teach a lot of the skills that we want to see kids developing when they're learning sciences. It was fascinating."

Not all pupils enjoyed physics. "For some kids, physics wasn't their thing – it's not what drove them," he says. But he regarded it as "an absolute privilege" to teach students who were engaged with the subject, especially those who went on to study physics at university. One ex-pupil even contacted Robertson after he became an MP to say she'd just passed her PhD. "She'd dropped a note into her thesis thanking Mr Robertson for being an inspiring physics teacher."

Political moves

Robertson's time at Great Barr came to an end in 2016 when the school was making job cuts and he accepted voluntary redundancy. After doing supply teaching for about a year, he got wind of a post at the NASUWT teachers' trade union, which he'd been school rep for at Great Barr. "It was one of those jobs I'd have regretted if I didn't apply for it," he says.

It was while working for the NASUWT that Robertson got involved in local politics. He joined the Labour Party and in 2019 was elected to Lichfield District Council, which was then run by the Conservative Party. He also stood in that year's UK general election, but was beaten by Michael Fabricant, losing by more than 23 000 votes. "I don't talk about that result," Robertson jokes.

Robertson is now one of more than 400 Labour MPs and spends most of his time on local Lichfield matters. "My number one focus is very much what's going on in my constituency, and that will always be the case," he says. "But I'm very fortunate to be one of a very small number of parliamentarians who've got a science background, let alone a physics background."

That interest saw Robertson host an exhibition in the Houses of Parliament, organized by the Institute of Physics (IOP), in June 2025 to support the International Year of Quantum Science and Technology (IYQ). "Every MP and member of the Lords would have been able to walk past and see that it was the IYQ," he says. The exhibition was, for him, a great opportunity "to show decision-makers that the UK is one of the world leaders in quantum".

That month Robertson also hosted a hands-on display of quantum technology for MPs and members of the House of Lords, again organized by the IOP. At the end of 2025 he sponsored another parliamentary reception, this time for physics-based companies that had won IOP Business Awards. "The event was absolutely wonderful," says Robertson. "Seeing some of the cutting-edge science from companies on show was astonishing."

Robertson's focus on science extends to his membership of various cross-party parliamentary groups, including ones about nuclear energy and space. He is also chair of a new group he has set up devoted to quantum science and technology. As a backbench MP, Robertson cannot dictate or implement policy, but he says such groups "can help build up a critical mass of interest in parliament to

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It’s the responsibility of me and other MPs with a scientific background to spark an interest in physics
Dave Robertson MP

drive an agenda forwards”.

With his background in teaching, Robertson is also keen to highlight the UK-wide shortage of physics teachers. While at Great Barr School – now rebranded as Fortis Academy – he was lucky. “I remember having a physics group meeting,” he says, “where there were six of us around the table and thinking ‘This is more [physics teachers] than most cities have’.”

As a 2025 IOP report pointed out, a quarter of state schools in England have no specialist physics teachers. In fact, more than half of physics lessons for 14–16 year olds are taught by teachers who never studied a physics-related subject beyond the age of 18. Despite some improvement, only 31% of the government’s target number of physics teachers have been recruited, while 44% of new physics teachers quit within five years.

Robertson admits that getting the lack of physics teachers on the radar is an uphill battle. “There are 650 MPs but have they all thought about the importance of getting more physics teachers in the classroom? Probably not, if I’m honest. That’s why it’s the responsibility of me and other MPs with a scientific background to spark an interest in physics and unearth the next Paul Dirac or Isaac Newton.”

Robertson would also like to get on the influential science innovation and technology select committee to spread the message about the importance of physics. But he is wary of spending too much time in parliament with other MPs with a scientific background. “It’s more helpful if all of us have tentacles that spread out into other groups and parties and sections of parliament.”

Spreading the message

For the wider physics community, Robertson believes that physicists need to speak out more strongly about how they can tackle many of the world’s problems, notably climate change. “It’s the biggest issue at the moment and a lot of the solutions are going to come from physics,” he says. “Getting more physicists engaged with decision-makers will not only be good for the future of the economy but ultimately for the future of the planet.”

As for Robertson’s own future, he knows that a career in politics is precarious. Voters rarely hold politicians in high regard and will often boot them out on a whim. It’s therefore hard for any MP to have a predictable career path or plan too far ahead. Robertson himself admits to having “no big aspirations” to be a cabinet minister, which is perhaps just as well given that his majority at the last election was so thin.

With the next general election not due to take place until 2029, Robertson is for now focusing squarely on his role as a backbench constituency MP. “The job I have is just about the most wonderful in the world,” he says. “I want to keep doing it because there’s some wonderful things I can do for my community, whether it’s physics, quantum or football.” But if Robertson did get kicked out, at least he can go back into the classroom.

“Rumour has it, we could do with a few more physics teachers.” ■

Barry Willis Photography

Barry Willis Photography

Spreading the word Former physics teacher Dave Robertson (top, and bottom left) at an Institute of Physics event that he sponsored at the Palace of Westminster in June 2025 to inform parliamentarians, including fellow MP Steve Yemm (bottom right), of the commercial applications of quantum science. The event formed part of the International Year of Quantum Science and Technology.

Trading places: meet the physicists in finance

iStock/peshkov

Market leaders Physicists, with their mathematical and analytic skills, can be very successful working in quantitative finance.

Tushna Commissariat talks to five physicists who pivoted to a career in finance, highlighting how they switched, exploring what skills they use day to day, and seeking advice for today's physics graduates looking to follow in their footsteps

It might not seem obvious at first glance, but physics and finance have much in common – especially at the frontiers of quantitative analysis. Both fields use mathematics, data and computational models to tackle complex systems. Physicists are trained to build models that test hypotheses, all while embracing the idea of inherent uncertainty and a rapidly changing environment.

Financial markets are much the same, as they constantly change and evolve as data flows in, feedback loops are formed, and fast-paced decisions are made. As a physicist, there is a natural overlap between the skills that finance firms are looking for, and your academic training and abilities.

The idea of using physics to make sense of financial markets is not even that new. It has been around for over a century, with one of the earliest examples being attributed to French mathematician Louis Bachelie developing his "Theory of Speculation" in 1900, which used the concept of a random walk to analyse fluctuations in the Paris stock exchange.

Modern quantitative finance covers a wide range of subjects, all of which involve using mathematical and statistical methods. Most physicists can therefore adapt to working in this sector, provided they have some additional training. Traditionally, "quants" – quantitative analysts working across investment, markets, research and risk – get involved in option pricing and risk, requiring stochastic calculus, Monte Carlo techniques, and solving partial differential equations. Today's quant roles more commonly involve supporting algorithmic or systematic trading; using data analytics, machine learning, and statistical and optimization methods.

Almost every one of these roles requires coding skills, especially when implementing models and algorithms in specific areas. Furthermore, the use of generative artificial intelligence (GenAI) to drive or enhance software development is now becoming standard. Physicists in the finance sector may also end up working as software developers, traders, risk managers and investment bankers.

To get a better idea of what it means to make this move from physics to finance, *Physics World* caught up with five professionals who went from the lab to the trading floor – some recently, some many decades ago. Antonia Lim, Benjamin McRoberts, Ashreya Jayaram, Sean Chang, and Han Lee reflect on how their careers evolved, and explain the skills they carried over from physics. They also look back on the trade-offs they encountered along the way and offer advice to today's graduates seeking to carve out their own careers in the sector.

Antonia Lim

Antonia Lim is chief investment officer (CIO) at global investment advisory firm Impact Cubed, which she joined in 2024. With 25 years of experience transforming investments and businesses, Lim began her career at Kleinwort Benson and Dresdner Bank (now Commerzbank), before going on to become global head of quantitative research at Barclays and then head of quantamental investments at Schroders. Lim holds an MPhys (masters of physics), specializing in theoretical and quantum physics, from the University of Oxford, UK. She is also independent chair of Weatherbys Private Bank's investment committee and board advisor, and a member of the CFA Research and Policy Centre's technical committee.

I loved the four years I spent at Oxford, as well as the sheer intellectual breadth of physics: it trained me to move between abstract ideas, mathematical models and real-world questions, which is something that has stayed with me throughout my career. To me, physics is a wonderful mix of understanding how things really work, puzzles, maths and creativity.

The move into finance was not part of a grand plan. With hindsight, it started with my MPhys research project within a very popular part of the condensed-matter department, affectionately known at the time as the "Chaos Lab", which was essentially the financial modelling department in physics. I was interested in the modelling and coding, and my dissertation focused on option-hedging strategies [techniques used to reduce investment risk] with transaction costs.

It was my first real exposure to the idea that methods rooted in physics could also be used within markets and decision-making under uncertainty. What appealed to me most was


Impact Cubed

the modelling itself: taking a messy real-world problem, making sensible assumptions, and then testing how well the model works. After graduating, I ultimately chose to join a private bank because I thought it would be interesting and fun, though I was very close to accepting a role in defence engineering.

I'm now CIO at Impact Cubed, where we develop customized indices, analytics, tools and data capabilities with a strong sustainability focus. Although I do not use the specific content of my physics degree day to day, I use the methods and habits constantly: mathematical reasoning, structured problem-solving, comfort with complexity, and the discipline to test whether an answer is plausible before trusting it.

> Physics also taught me to properly define a problem before trying to solve it. That sounds simple, but in finance it is incredibly important

Physics also taught me to properly define a problem before trying to solve it. That sounds simple, but in finance it is incredibly important, whether you are building an index, designing an investment process, or challenging a model that is elegant mathematically but too far removed from the real world.

On the softer-skills side, physics gave me confidence in tackling unfamiliar problems and explaining technical ideas clearly. Over the years I have worked with people from many different disciplines, and one of the most valuable skills has been translating between technical precision and practical decision-making.

Finance can be intellectually stimulating because the problems are constantly evolving, and impact society at large. I've held the very serious responsibility of investing the livelihoods of millions of people. Within the quant sphere, there is a really strong community of people who enjoy models, evidence and rigorous thinking, so in that sense it can feel very familiar to physicists. Indeed, when I joined the London Quant Group decades ago, it felt like home straight away.

The pointy end of finance is shaped by market cycles and commercial pressure, which creates a degree of individual uncertainty that some can find draining. But if you enjoy solving practical problems and working at the intersection of theory, data and human behaviour it is an exciting place to build a career.

My advice to graduates looking to join finance today would be to not worry too much about making a perfectly linear plan. Physics gives you a very transferable toolkit, and there are already many physicists in finance, particularly in quantitative roles, so it is a move that can feel surprisingly natural.

Benjamin McRoberts

Benjamin McRoberts is head of European power engineering at Citadel. He spent the last decade working at Goldman Sachs, most recently as the head of EMEA Commodities Strats. McRoberts studied mathematics and physics the University of Bristol in the UK. He also completed an MSc in financial mathematics at the University of Warwick.

During my BSc at Bristol, I realized pretty early on that I preferred the theoretical side over the practical, and I switched to the joint honours MSci mathematics and physics course after my first year. This allowed me to replace some of the experimental physics courses with more of a mathematical physics focus so I could study concepts such as applied partial differential equations, fluid dynamics and quantum information theory.

My final year master's dissertation focused on the "weak measurement" quantum mechanical phenomenon, and while I explored the idea of doing a PhD after my master's, I ultimately fancied a change of scenery. I also found the open-ended nature of pursuing further academic research a little bit daunting, and I wasn't ready to commit another four years or so to something I wasn't totally sure about.

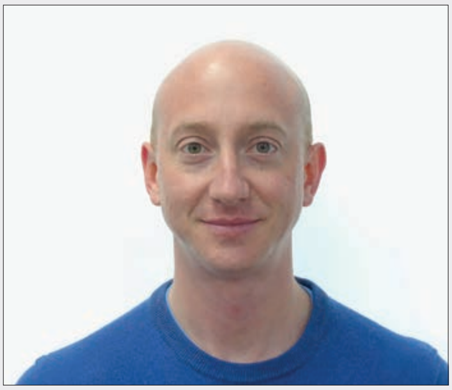
I had a sense that finance might provide some interesting quantitative problems that I could use my educational background for, and I was likely influenced by a careers fair hosted by my university. I did consider a few other avenues such as technology consulting and teaching, but ultimately the large annual graduate intake for investment banking in London appeared to provide the most opportunity.

After applying for a series of summer internship programmes at the end of my third year, I secured an offer from the Australian investment bank Macquarie. That summer I worked within their infrastructure funds business, which raised investment capital from large asset managers and pension funds, investing it in infrastructure projects across Europe, such as airports, toll-roads and utilities. That internship led to a full-time graduate offer that I gladly accepted, kicking off my graduate career in finance.

I worked at Macquarie for a year but decided to build my skills with a master's in financial mathematics at Warwick. While I was contemplating if this was the right path for me, I read a book by particle-physicist turned quant Emanuel Derman, titled *My Life as a Quant: Reflections on Physics and Finance*. It really captivated me and I still highly recommend it, especially for those with a physics background considering a career in finance.

During that degree, I built on some of the basics of probability and statistics I'd learned on my undergraduate course, to cover new topics like stochastic calculus and derivatives pricing. I also got more of a taste of computer programming, through a module focused on C++ which I really enjoyed. I quickly realized that I had made a good career choice by going back to university.

After leaving Warwick, I spent two years as a quantitative analyst at a commodities trading firm before joining Goldman Sachs in their "commodity strategies" group in London. Over the last decade I've worked across their commodities complex – from precious and base metals to power and gas, and oil products – covering derivatives pricing/modelling, trading tools and analytics, as well as automated trading.


Benjamin McRoberts

Your formal scientific training coupled with an appreciation of real-world applications gives physicists a fantastic foundation for such a career

Last year, I had the opportunity to join the US-based multinational hedge-fund and financial services company Citadel. I was extremely impressed by the calibre of people I met during the interview process, and similarly since joining the company. This, together with the firm's reputation for its rigorous and sophisticated investment approach, gave me the confidence that it was the right move for me.

Since finishing my master's, I've consistently made use of my technical educational background. Sometimes that's been explicitly – using skills from linear algebra, calculus and differential equations – but sometimes indirectly from generally learning to be better at abstract problem solving and not giving up when faced with a difficult intellectual challenge.

What I've loved the most about working in the commodities markets is having the ability to use sophisticated mathematical techniques to solve problems in the real world. On the flip side, it's a demanding and fast-paced environment, which requires commitment and tenacity to succeed.

What has sustained me throughout is a real passion and enjoyment for what I do. You typically get to work with a group of talented and motivated individuals. There is a strong feeling of camaraderie and shared pride in your work, which is something I've always appreciated.

For physics graduates looking to get into the finance, remember that physicists typically make great quantitative finance professionals. I've worked with and hired many and they tend to do very well – partly thanks to their willingness to find creative and varying solutions to any problem. Your formal scientific training coupled with an appreciation for a whole swathe of real-world applications gives physicists a fantastic foundation for such a career.

Ashreya Jayaram

Ashreya Jayaram is a quantitative strategist in the corporate and private bank division of Deutsche Bank. She did her PhD in physics at the Johannes Gutenberg University of Mainz, Germany, focusing on the theory of biologically-inspired nonequilibrium systems. After a postdoc at the University of Stuttgart, Jayaram moved to a career in quantitative finance at Wells Fargo, before taking on her current role at Deutsche Bank.

My decision to move from physics to finance came when I realized I was not suited to an academic career and instead I began looking out for options in industry. I was looking into avenues where I could continue to build useful models that capture real-world observations, which was a part of my academic career that I most enjoyed. This led me to quantitative finance.

To understand if quantitative finance was my cup of tea, I used online resources to educate myself about financial markets and the kind of models practitioners use to describe them – and here I am today. A key skill that I developed during my physics degree that is applicable in my job now is the ability to break down complex problems into simpler and more tractable forms. It's also important to identify the vital elements that drive the behaviour of observables of interest (for example, profits) – a skill that is systematically developed in theoretical physics.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What excites me most about my job today is the dynamic and unpredictable nature of financial markets

Another useful skill is the ability to manage multiple projects simultaneously with different collaborators. I also have to communicate effectively with diverse audiences of varying backgrounds, which is an ability I developed during the course of my PhD and I believe helps me in my current role.

What excites me most about my job today is the dynamic and unpredictable nature of financial markets. Their far-reaching impact on everyday life creates a high-energy work environment, which I find both engaging and enjoyable.

If you're looking to move into the field, my advice would be to find out more about the different roles in the financial world and the diverse range of skills they demand. For physicists with no exposure to finance, it would beneficial to read about what you might enjoy working on, and look into some self-formulated projects and internships to see if it does align with your interests.

Sean Chang

Sean Chang is a quantitative researcher at Citadel Securities. Chang completed a PhD in condensed-matter physics at the University of British Columbia, Canada before moving into the financial sector.

My PhD focused on low-dimensional condensed-matter theory, and while I enjoyed the research, my advisor was not very supportive, and I decided not to take on a postdoc. While I was struggling to find what to do after I graduated, I met someone from my department who had graduated the year before.

He introduced me to the idea of being a quantitative analyst, as the role mostly involved solving partial differential equations. He recommended some books I could read on the topic and then offered me a job at a local financial software company FINCAD (now Numerix) as a quant. After a few years at the company, I spent the next decade or so at Citibank and later at Bank of America Merrill Lynch. Six years ago, I joined my current

The skills that are much more useful and transferable revolve around scientific thinking and the ability to tackle a hard problem

company, Citadel Securities in the UK.

The whole quant industry changed profoundly after the 2008 financial crisis. Before the crisis, it was mainly about how to price a complicated financial contract using fancy models. But now the industry has moved towards algorithmic electronic trading on simple vanilla products. So at the beginning of my career, there was a lot of focus on pricing theory. Now it's more data analysis and how we can improve algorithms.

I don't use any technical skills from my physics degree in my day-to-day job (although maybe one day we will find some practical quantum field theory application to finance). Most of my work instead involves software engineering, which I didn't learn much about during my physics degree. But the skills that are much more useful and transferable revolve around scientific thinking and the ability to tackle a hard problem.

Many people think that a job in finance is stressful and that we have a bad work/life balance. I feel it's a lot less stressful and much better balance for me personally – in fact, I realized soon after my first job that most of us don't work during the weekend, which was great.

If you're considering a career as a quant, I would recommend doing your research to find out more about the whole sector in general and see if it aligns with your abilities and your needs. And never stop learning!

Han Lee

Han Lee is co-founder of RLXPartners, a technology-startup venture consulting and investment firm. He has a PhD in theoretical physics from the University of Cambridge, UK, where he worked on quantum many-body problems in condensed matter. Lee has previously had numerous leadership roles in finance, most recently as global head of quantitative strategies and automated trading for the fixed income division at Morgan Stanley. Before that he was global head of quantitative analytics at RBS.

When I started in the financial sector in the early 1990s, quantitative and mathematical finance was still a relatively new field, albeit one that was rapidly growing. It coincided with a major expansion of the financial markets, in particular the increasing complexity in financial derivatives. These changes provided many opportunities and challenges, which sounded interesting to me.

At the same time, the industry was actively seeking to find quantitative analysts with physics, maths or engineering backgrounds, which made the decision for me to move into finance straightforward. The sector still looks to hire physicists and those with a scientific background, but it has become much more competitive.

When it comes to skills from my physics background, both problem solving and scientific intuition are very transferable. Having the ability to harness familiar mathematical methods or programming techniques – or

Han Lee

quickly learning new ones – to solve problems is a core component of the work. Physics also teaches a powerful combination of rigour when required, and an understanding of how and when to use approximations and estimations. Critical soft skills include communication and teamwork.

The pros and cons of a career in finance are straightforward. People are usually aware of very high starting salaries, especially in banking and hedge funds, as compared to staying in academia. Less well-known is how quickly this can increase once you progress

It can also be a very exciting and stimulating work environment, and can be very rewarding to see your work leading directly to results that have immediate impact

and gain experience.

It can also be a very exciting and stimulating work environment, and can be very rewarding to see your work leading directly to results that have immediate impact. Potential challenges or downsides are that there is a relatively intense and competitive working culture, which can bring stress and some uncertainty; which won't suit everyone.

Furthermore, not all physics graduates and postgrads might want to move to a completely different field. Although finance can have interesting and complex problems to work on, the focus is quite different from working in academia. The latter would allow for a much higher degree of intellectual freedom, and some would consider this not only intrinsically valuable but also capable of having a significant and wider positive impact.

STEM stock rising in quantitative finance

Susquehanna is a premier options trading firm, but it is also a place that captures the spirit of academia, where researchers are free to pursue innovative ideas, learn new skills, and solve highly complex problems

Susquehanna

Quantitative trading plays an ever-increasing role in the global financial markets. Automated algorithms analyse millions of financial instruments simultaneously, while mathematical models anticipate price movements on nanosecond timescales.

Susquehanna is a proprietary trading firm, meaning it invests its own capital in the markets. Susquehanna's quantitative researchers – or "quants" – collaborate with traders and technologists to drive the company's success. Quants design and implement the complex models and algorithms the firm needs to make rapid, well-informed pricing and trading decisions.

The quant advantage

Lyubo Panchev, a quant at Susquehanna with seven years at the firm, describes how quants collaborate across a wide range of instruments and problem types. "Our quants are all trying to mathematically understand the world and the financial markets," he says, "and then we use that information to determine whether we want to make a trade or not." While the challenges vary considerably across the firm's different trading desks, that shared mathematical mission is what unites them.

The details of this work can differ from quant to quant, from devising new pricing approaches for financial instruments, to finding patterns in data to turn into trading signals, to developing specialized software to implement new trading strategies.

However, specialist knowledge in specific fields is not what Susquehanna is primarily interested in when hiring a new quant. Instead, the firm is looking for the types of transferrable skills that PhD students in STEM fields often possess. "We want to hire people who can reason through first principles and feel comfortable working in an uncertain environment with open-ended questions to which answers sometimes might not even exist," says Panchev. "So that's why we like to hire PhDs."

A physicist, for instance, brings the skills and intuition for modelling systems with incomplete information – whether that's modelling interactions in a complex system or inferring signal from noise in a vast dataset. The mental frameworks used by a theorist studying quantum field theory or an experimentalist analysing data translate surprisingly well to pricing derivatives or spotting anomalies in market behaviour.

Life outside academia

Panchev – a three-time International Mathematical Olympiad medallist with a PhD in pure mathematics from MIT – says that the most satisfying part of working at Susquehanna for him is that it preserves what he loved about academia, while at the same time addressing some of the shortcomings.

"The freedom to work on what you want is a unique advantage in academia, over pretty much any industry," says Panchev. "But what quant researchers do at Susquehanna is close to that spirit."

Though he enjoyed focusing on challenging questions surrounded by like-minded people, he found working on hyper-specialized academic problems during his PhD a slow, lonely slog. At Susquehanna, quants work on challenging problems, but never in isolation. Quantitative trading problems are invariably interconnected, requiring close collaboration between researchers, traders, technologists and many other experts, to connect all the pieces together.

What's more, the environment is highly dynamic. "The impact is much more immediate, sometimes instantaneous," he adds. "You can be looking at the data and then decide to make a change to your algorithm, tweak a few things, and five minutes later, you're already getting data that's from the change you just made – it's a very fast feedback loop."

When you add a highly desirable salary, benefits package, career development opportunities, and a company culture that values strategy games like poker to hone decision-making skills and apply them to complex financial markets, it is clear to see why a STEM PhD student might choose Susquehanna over a career in academia.

From toy problems to market mastery

To earn a seat at this table, applicants are put through their paces. The first and perhaps greatest challenge they face is getting through the interview process. Quant skills – like original thinking, intuition, and problem-solving – are not easily described in a CV or interview, they need to be demonstrated. But how can an applicant demonstrate those skills in an interview?

"We build interesting toy problems that are representative of what we do," explains Panchev. "And then we give them time to think and work on it on their own, before reconvening to see how they approached the problem, and what they found out."

Successful applicants who are hired on immediately participate in a comprehensive 10-week internship – the first step in an intensive front-loaded education program at the company. This internship builds solid foundations in finance domain knowledge, machine learning, programming, data analysis, as well as what Susquehanna's different quant groups do and how their work all fits together.

The internship builds solid foundations in finance domain knowledge, machine learning, programming and data analysis

Susquehanna

Lyubo Panchev

Panchev says that a typical direct full-time hire requires five months or more of very structured education, over time, however, the quant will be faced with more open-ended problems and need to chart their own way, free to explore their own ideas and methods.

"There's a long, steep learning curve but at the end you become an expert," he adds. "In a way, it's very similar to how a PhD is structured." This means that, while the barrier to entry is fairly high, the support system is robust, with a well-organized education program that ensures that everyone is equipped with the tools that they need to succeed.

For the successful STEM PhD student assessing their career options, Susquehanna offers a compelling proposition – the chance to remain a scientist, but on a stage where the stakes are higher, the collaborations deeper and more dynamic, and the results play out in real-time and have real-world impact.

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Ask me anything: Giannis Zacharakis

Giannis Zacharakis is a research director at the Institute of Electronic Structure and Laser (FORTH) in Greece, where he leads the Laboratory for Biophotonics and Molecular Imaging.

Giannis Zacharakis

Zacharakis has served as president and vice-president of the European Society for Molecular Imaging. His main focus is on developing key enabling technologies for imaging biological processes in living systems.

Zacharakis is also the CEO of the precision photonics spin-off Kymatonics. The company recently secured a highly competitive €2.1m European Innovation Council (EIC) Transition Open grant, to advance the development and commercialization of their innovative wavefront-shaping objective lens.

What skills do you use every day in your job?

My everyday work involves both hard and soft skills, which are equally important for a successful career.

At its core, my work is about asking questions and defining the path to discovery, through scientific knowledge and rigour. This requires being able to break down complex physical and biological problems into manageable and measurable components under certain hypotheses. Much of my day therefore involves analytical thinking and judgement: evaluating whether an observed effect is physically meaningful or an artefact of instrumentation or data processing. That defines the path forward.

Problem solving constantly requires creativity and thinking out of the box, because experiments rarely behave exactly as planned. You need patience, persistence and the ability to stay calm when instruments misbehave or data contradict expectations.

Communication is another central skill. I regularly explain technical concepts to students, collaborators from other disciplines, and biologists or clinicians who may not share the same vocabulary. Translating physics into accessible language, without oversimplifying the science, is something I consciously practise and it takes time and effort to achieve.

Project management also plays a surprisingly large role. Co-ordinating experiments, supervising students, meeting deadlines for proposals or manuscripts, and balancing long-term research goals with short-term deliverables requires structured planning.

Finally, mentoring is an important part of my routine. Guiding students and young scientists through experimental design, encouraging independent thinking, and helping them develop scientific confidence is both a responsibility and an integral component of academic work.

Essentially, while physics provides the foundation, my job relies on a blend of analytical rigour, practical problem-solving, communication and leadership.

What do you like best and least about your job?

What I value most is intellectual freedom: the ability to pursue questions that genuinely interest you is a privilege. There is something deeply satisfying about seeing a concept move from hypothesis to experimental evidence. Even incremental progress can feel meaningful when it clarifies a mechanism or resolves ambiguity.

I also appreciate the interdisciplinary environment. Working at the interface of physics, biology and biomedicine forces me to continuously learn and think beyond boundaries. It prevents intellectual stagnation and keeps curiosity alive.

Mentoring students is another highlight. Watching someone gain confidence, moving from following instructions to proposing their own ideas, is deeply rewarding. Research training is not only about technical knowledge; it is also about developing judgement and rigour.

On the more challenging side, uncertainty is a constant companion. Funding cycles; competitive grant applications and proposal rejections; and the unpredictability of research outcomes can be demanding. Not every idea works, and not every effort translates into immediate output. Maintaining momentum despite setbacks requires persistence and resilience.

> The ability to pursue questions that genuinely interest you is a privilege

Administrative responsibilities can also fragment time and reduce deep focus. Balancing research, supervision and institutional duties often requires careful prioritization.

What do you know today, that you wish you knew when you were starting out in your career?

I wish I had understood earlier that uncertainty is not a sign of inadequacy but is the natural state of research. Early in my career, I expected clarity to come quickly if I worked hard enough. In reality, meaningful progress often requires extended periods of ambiguity. Learning earlier to tolerate that and even see it as productive would have reduced unnecessary self-doubt.

I also underestimated the importance of communication. Being technically correct is not enough; ideas need structure, clarity and narrative. Writing well and presenting clearly are not secondary skill; they are core scientific tools.

Another lesson is that collaboration is essential. Scientific progress increasingly happens at disciplinary boundaries with impactful discoveries emerging at interfaces. Engaging with people who think differently challenges assumptions and strengthens work.

Finally, remember that career paths are less rigid than they appear. There is rarely a single "correct" trajectory. Developing transferable skills, analytical thinking, adaptability, mentoring and project management provides resilience across different opportunities.

I would tell my younger self to focus less on short-term milestones and more on building depth, clarity of thought and professional relationships. Those foundations endure longer than any single milestone.

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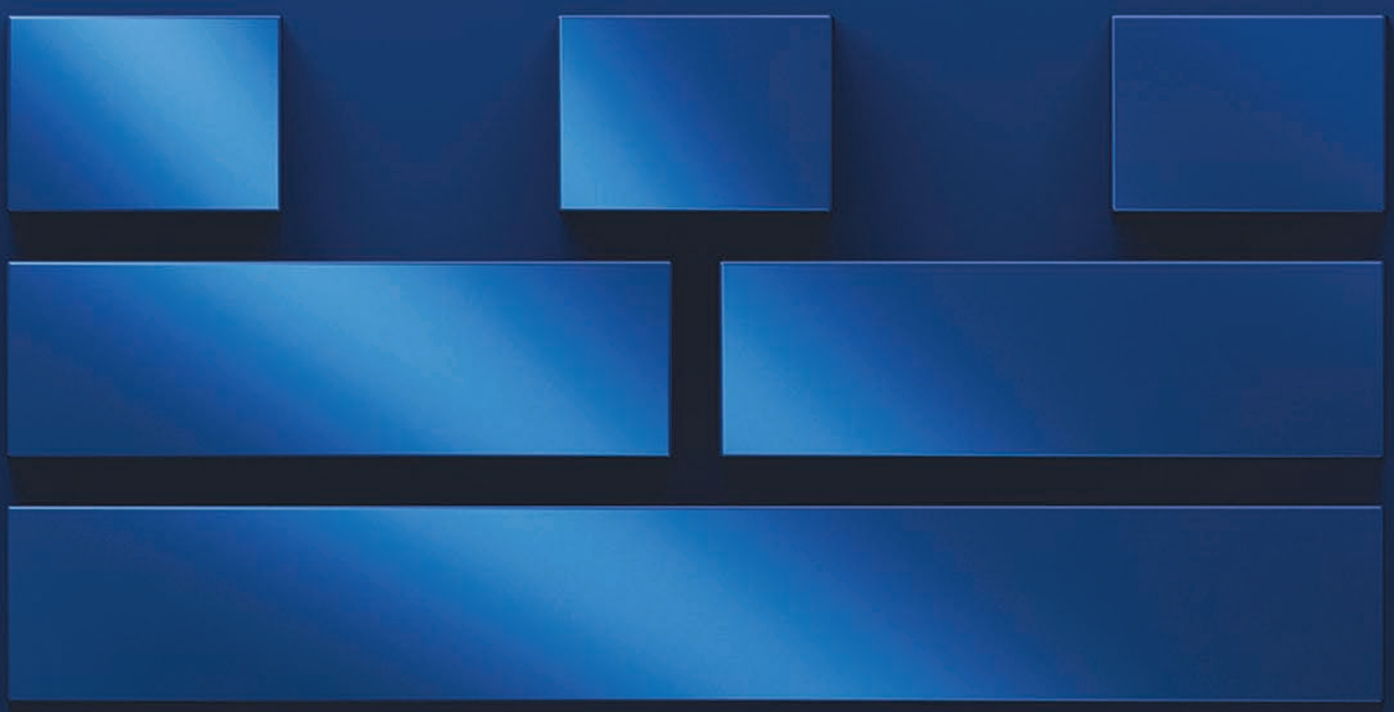
Stable Signals

There are six horses labelled 1 to 6 with distinct running speeds.

Alice knows the speed rankings of the horses and will encode the information into a positive integer n in the range [1, t] that she will tell Bob.

Eve then picks either the fastest or slowest horse, tells Bob the ID of the horse, and asks Bob to guess whether the horse is the fastest or slowest.

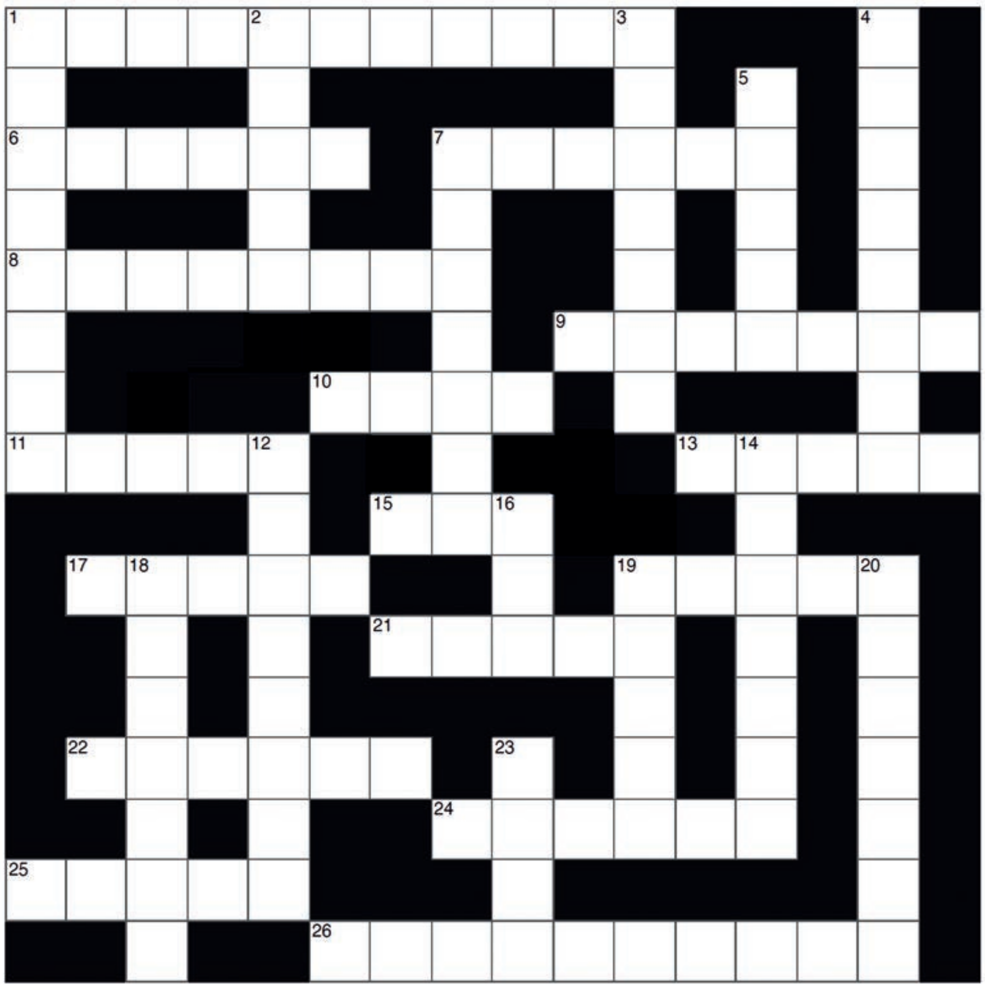
What is the minimum value of t such that, based off the given integer n and the encoding scheme Alice and Bob created beforehand, Bob is always able to answer correctly?



So you think you know geophysics?

Test your knowledge of the geophysical impact on the Earth's climate with this quick crossword. Most of the clues are based on the recent *Physics World* feature by Michael Allen (March pp46–52), which examined how global warming could cause extreme changes in earthquakes and volcanic activity. There are a few additional brain teasers thrown in.

If you'd like to fill the crossword in online (and check your answers) go to our new interactive puzzles area at **physicsworld.com/puzzle**.



ACROSS

1 ________ flow: fast currents of hot gas and volcanic matter (11)
6 The force per unit area on rock (6)
7 ________ lava: formed when lava erupts underwater or flows into the ocean (6)
8 ________ plates: mobile sections of the Earth's crust (8)
9 Teardrop-shaped hill formed by glacial ice deposit (7)
10 West Antarctic ________: sits beneath the West Antarctic Ice Sheet (4)
11 A division of time within a period, used to categorize Earth's history (5)
13 Gaps within rock in which pressure builds when water percolates down (5)
15 Abundant in polar regions and above the snow line; can form glaciers (3)
17 Flaw in character, or in the Earth's crust (5)
19 ________ Dam: reservoir in India influencing seismicity during monsoon (5)
21 ________ layer: thin, protective shield of gas in Earth's stratosphere (5)
22 North American volcano: Mount St ________ (6)
24 Fast-moving, destructive volcanic mudflows (6)
25 Narrow, sharp-edged mountain ridge formed by glacial erosion (5)
26 Continent holding about 70% of the world's freshwater reserves as ice (10)

DOWN

1 ________ degree days: term for days above freezing in the Alps (8)
2 Peruvian city located in a high-seismic region of the Central Andes (5)
3 Large hollow formed when a volcano collapses inwards, e.g. Yellowstone (7)
4 Explosive type of magma rich in silica (8)
5 Seismic ________: a localized cluster of earthquakes (5)
7 Ocean surrounded by the Ring of Fire (7)
12 The current interglacial interval of the Quaternary Period (8)
14 ________ Mons: largest volcano in the solar system (7)
16 ________ sphere: area on and around the Earth where life exists (3)
18 Los ________: US city at risk of earthquakes (7)
19 The East African Rift system runs through this country (5)
20 World's driest non-polar desert, it features salt flats and volcanoes (7)
23 Large volcanic island that produces good coffee (4)